REVOLUTIONARY CONCEPTS OF RADIATION SHIELDING FOR HUMAN EXPLORATION OF SPACE

Report from the Workshop held
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REVOLUTIONARY CONCEPTS FOR HEDS RADIATION SHIELDING

Executive Summary

At their present state of development HEDS (Human Exploration and Development of Space) mission architectures, radiation transport theory and radiobiological research indicate the need to add massive shielding to manned deep space vehicles and surface habitats if the radiation dose limits are similar to those in use for low Earth orbit missions. If conventional spacecraft materials launched from Earth provide this extra shielding, it will substantially increase the mission costs. In this workshop we examine revolutionary ideas for shielding that would mitigate these costs.

None of the revolutionary new ideas examined for the first time in this workshop showed clear promise. The Workshop felt that some concepts previously examined were definitely useful and should be pursued. The Workshop also concluded that several of the new concepts warranted further investigation to clarify their value.

The Workshop recommends the use of *in situ* materials for shielding surface habitats and encourages further investigations of this approach. The use of surface terrain for added shelter should be pursued with detailed investigations.

Some unconventional spacecraft materials deserve further study. Polyethylene is definitely useful as shielding. Research should be pursued to find ways to fabricate functional spacecraft parts from it. Borated polyethylene should be re-evaluated for its shielding effectiveness using improved radiation transport codes.

Two other categories of materials warrant continued research. Continuing research on carbon nano-materials should be monitored for improved hydrogen storage capability. The radiation shielding effectiveness of palladium-based alloys for hydrogen storage should be evaluated using existing radiation transport codes.

The Workshop noted that several mission architectures carry large volumes of liquid hydrogen as fuel. The Workshop feels that it would be prudent to consider using this liquid hydrogen as shielding for the crew because of its extraordinary shielding effectiveness.

It is recommended that some simple ‘rules of thumb’ for radiation shielding effectiveness of various materials be developed as guidance for mission designers.

The Workshop investigated the potential use of extra-terrestrial materials and space debris for shielding. While adequate material in all categories can be located in space, it was felt that all these concepts were impractical. The only one that might deserve further consideration is the use of space debris from geo-stationary orbit, but only if its collection and removal is necessary for other reasons.

While none of the electromagnetic concepts showed clear promise, the one which uses cold plasma to expand a magnetic field was recommended for further assessment.

The Workshop did not consider biomedical solutions such as radioprotectants or the implications for dose limits for microdosimetric theory, or mission architectural solutions such as shortened interplanetary travel times or a re-usable shield to be stored in geostationary orbit between missions.

In the report that follows we have tried to assess each of the revolutionary concepts and provide some clear guidance for future investments on research on radiation shields. We believe that some of the materials we examined show promise of lighter shields than could be made from conventional spacecraft materials. These concepts should be vigorously investigated. One of the concepts for electromagnetic shielding could not be evaluated in the time available. It should be properly assessed and pursued if it shows promise.

Introduction

At the request of NASA Headquarters, Code UG, a workshop was held at Marshall Space Flight Center (MSFC) to assess a list of "Revolutionary Physical Sciences Radiation Protection Strategies," (Appendix C) which had been assembled by the Headquarters Advanced Radiation Protection Working Group and other concepts found in the literature. For planetary missions the necessity of adequately shielding flight crews from the effects of galactic cosmic rays (GCRs) and solar energetic particles (SEPs) has been stressed in publications, workshops, and national committee reports. The principal problem is the interplanetary GCR flux which could produce radiation doses above currently allowable limits within the shielding provided by present-day manned spacecraft (e.g., ISS and STS).

The last recommended limit from the National Council on Radiation Protection (NCRP) issued in 1989, 0.5 Sv/year (or 50 rem/year) to the blood forming organs of flight crews, considered only the low-Earth orbit environment (dominated by trapped protons and electrons). The dose limit for the ISS has been administratively set at 0.2 Sv (or 20 rem) per year (Cucinotta, 2000). No limits have yet been set for planetary missions.

For HEDS, the implication of the current limits and the currently available radiation shielding calculations is that considerable mass for radiation shielding will probably have to be added to the transit vehicles and surface habitats beyond that which is required simply to perform the mission. Current research could affect both the limits and the shielding calculations. The carcinogenic effects of the high energy and heavy element (HZE) content of the cosmic ray flux, and its nuclear interaction products, are being investigated in the NASA Life Sciences Program. The methods used to calculate the secondary interaction products behind shielding are also being improved. Radiobiology research could affect the limits set for planetary missions, and the shielding calculation improvements might change the predicted biological risk for a particular shielding situation.

Interplanetary Radiation Environment

For space flights beyond the Earth's magnetosphere both crews and spacecraft equipment face a significant hazard from the natural ionizing radiation environment (Space Studies Board, 1996; Wilson, 1995; 1997). The most significant constituents of this environment are energetic protons and heavy ions during SEP events (Shea, 1990; Sauer, 1990) with energies up to a few 100 MeV, and GCRs (Badhwar, 1996; Wiebel, 1994; Nymmik, 1992), which consist of protons and heavy ions with energies in the GeV (billion electron volts) range.

The elemental composition of GCRs is about 85% protons, 14% alpha particles, and 1% heavier nuclei when compared at the same energy per nucleon (Wiebel, 1994). The effects of heavy nuclei far outweigh their number because their energy deposition is proportional to their nuclear charge squared and their biological effect enhances their importance even more. Figure 1 shows the energy spectra of selected GCR nuclei both for solar maximum and solar minimum (Badhwar, 1996). The low energy part (below ~1 GeV) of the GCR spectrum is modulated as solar activity increases and decreases over the solar cycle. This changes the total flux by about a factor of 3. There has been a continuing effort over many years to measure and model GCR fluxes. Current models (Badhwar, 1996; Wiebel, 1994; Tylka, 1997) represent the historical data base of measurements with accuracies of about 15 percent.

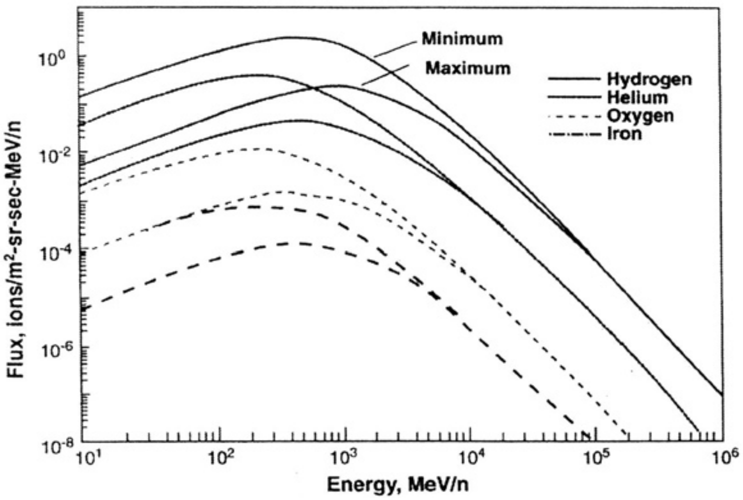

Figure 1. “Worst case” model cosmic ray spectra for solar minimum and solar maximum (Badhwar, 1996).

Solar Energetic Particle (SEP) events consist primarily of protons but include alpha particles, and heavy ions with a composition that varies from event to event (Shea, 1990; Sauer, 1990). Since SEP events are associated with active regions on the Sun, they are more frequent near solar maximum and a single active region may produce a few SEP events over a period of weeks. While the average particle energy for SEP events is lower than for GCR, the flux is much higher. Figure 2 (Shea, 1990; Sauer, 1990) compares the spectra of several of the largest events. Individual events last from a few hours to several days with most of the fluence in the first day. This makes it possible for “storm shelters” to be considered for the protection of flight crews.

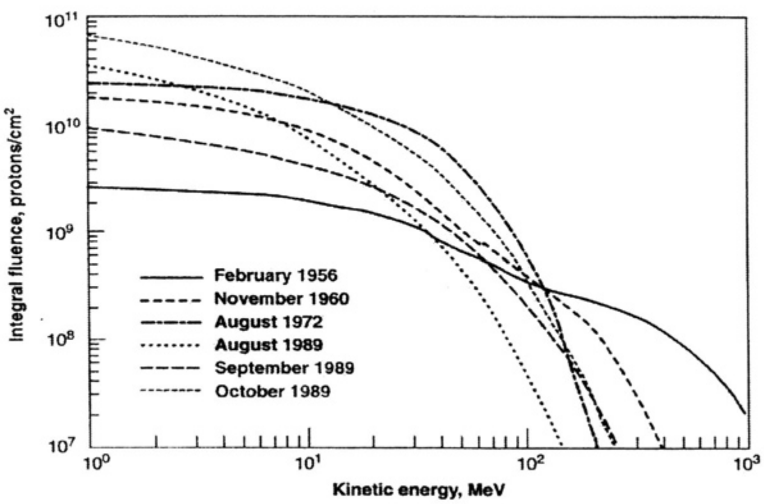

Figure 2. Spectra of larger solar particle events from 1956 to 1990 (Shea, 1990; Sauer, 1990).

Radiation Shielding with Materials

The potential impact of present day dose limits on HEDS mission architecture can be partially illustrated with results from published examples of shielding calculations. Figure 3 shows the calculated dose equivalent behind planar slabs of lunar regolith. It is assumed that the GCRs and the SEPs from all the events of 1989 combined are normally incident on the slab.

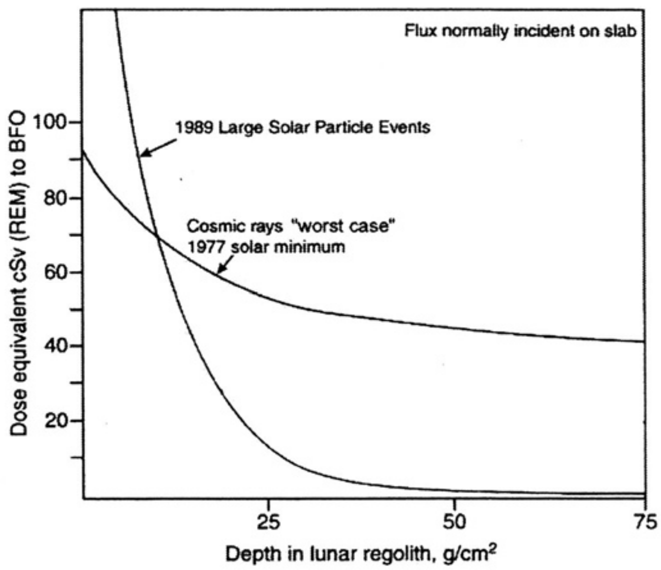

Figure 3. Annual dose equivalent to the blood forming organs in the computerized anatomical man model is shown beneath a variable thickness slab of lunar regolith for the GCR flux at solar minimum (Badhwar, 1996); and for the sum of the larger SEP events in 1989. (Wilson, *et al.*, NASA TP 3662, 1997). Uncompacted lunar regolith has a density of ~1.5 g/cm^3. Thus 75 g/cm^2 ÷ 1.5 g/cm^3 = 50 cm.

The main points illustrated here are: (a) the annual dose equivalent from GCRs dominates the 1989 SEP dose beyond regolith shielding depths of ~10-cm, and (b) these depth-dose curves flatten considerably as the shielding depth increases. The reason is that GCR protons and heavy nuclei, rather than stopping by ionization as do most SEPs, break up through nuclear interactions and produce cascades of secondary particles (Figure 4). We note here that many of the shielding calculations available in the literature assume the cosmic rays are normally incident on a slab of material, which is a reasonable way to compare different materials. In nature, the cosmic ray flux is isotropic, so three-dimensional calculations are required to predict the dose in spacecraft or surface habitats. Those calculations generally have steeper depth-dose curves (Simonsen, 1997).

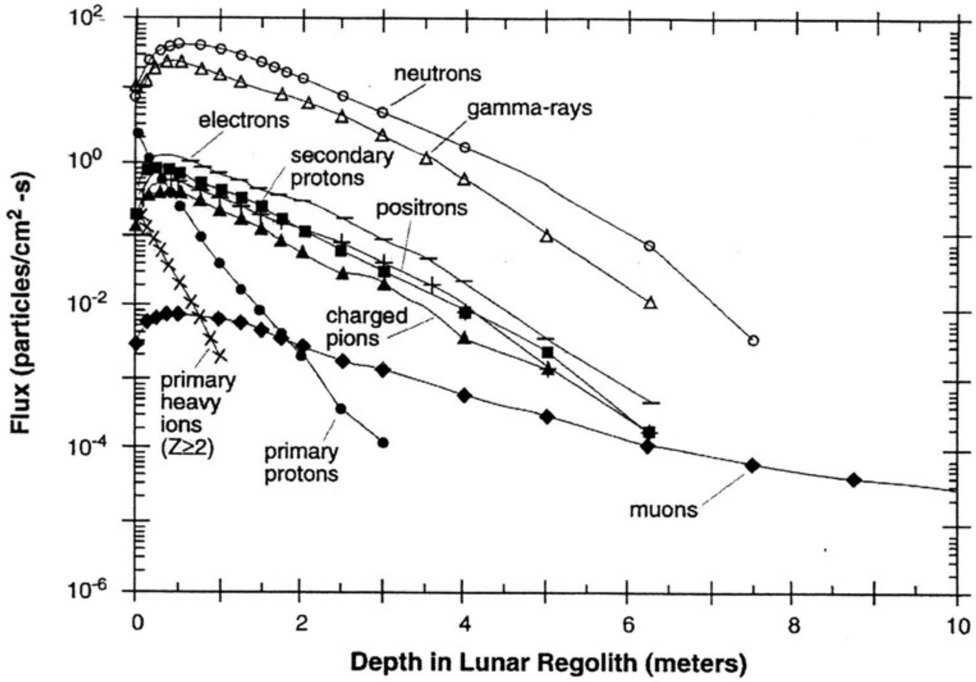

Figure 4. Calculation of primary cosmic rays and produced secondaries in lunar regolith. (Armstrong, 1991)

Figure 4 illustrates the composition of the radiation within lunar regolith as a function of depth. It can be seen that the incident fluxes of GCR primary protons and heavy ions quickly generate large fluxes of neutrons, gamma rays and other secondaries that diminish only slowly with depth. It is these penetrating secondaries that cause the slow fall-off of the dose equivalent seen in figure 3.

Figure 5 compares the radiation exposure rate for various materials as a function of their thickness in mass per unit area. From this figure, we can see that the materials with the smallest mean atomic mass make the lightest shields. There are several reasons for this. First, materials with low mean atomic masses simply put more nuclei in the path of the incident cosmic rays for the same shield thickness in mass per unit area, helping to break up the heavy nuclei. Second, lighter nuclei contain fewer neutrons (hydrogen contains none at all) so fewer secondary neutrons are created. Third, because these nuclei have a smaller nuclear charge they are less effective in creating secondary electrons and gamma rays by pair production and *bremstrahlung* respectively. Finally, some light nuclei such as carbon and oxygen, when struck by a cosmic ray tend to disintegrate into helium nuclei and produce no neutrons. The neutrons produce a component of the radiation dose that increases in importance with the atomic mass and depth of the shielding material.

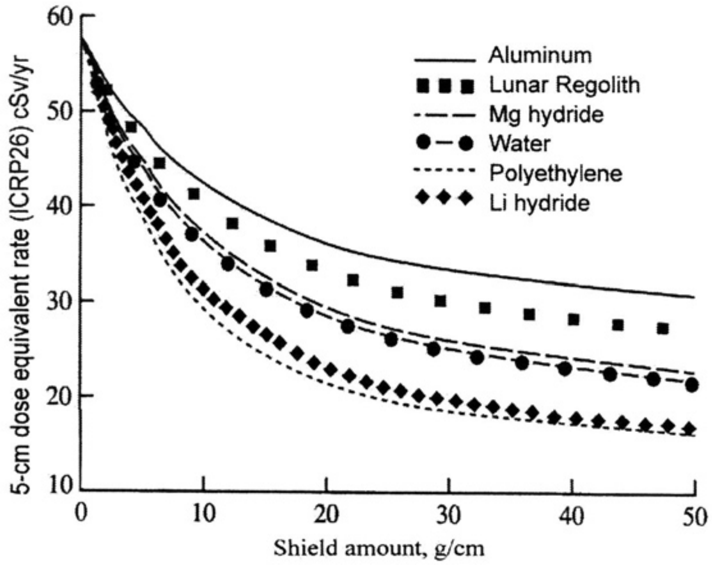

Figure 5. Dose at 5 cm depth in tissue for GCRs at solar minimum as a function of areal density for various materials (Simonsen, 1997). The GCR spectra used were from the "old" NRL CRÈME code (Adams, 1986). This explains in part the lower dose equivalent rates, partly due to not using the computerized anatomical man model.

Figure 5 illustrates how the dose equivalent 5-cm deep in human tissue (typical for the blood forming organs) is further reduced by shields made from various materials.

At the current state of mission architecture, shielding calculations, radiobiological research and radiation dose limits, the addition of radiation shielding mass to transit and surface habitats seems to be indicated, unless revolutionary new approaches to radiation shielding can be found.

The Workshop

This report evaluates numerous revolutionary concepts for HEDS radiation shielding. To evaluate these concepts a one and one-half day Workshop was held at Marshall Space Flight Center (MSFC). The shielding concepts that were evaluated included those in Appendix A and others found in the literature. The participants were selected to provide expertise on the scientific and technical aspects of these concepts.

NASA Headquarters' directions to this Workshop were to examine the physical shielding concepts that have been suggested, but not to address approaches using propulsion ("get there fast"), or possible solutions from medical science.

The Workshop concentrated on concepts for shielding from the galactic cosmic ray (GCR) flux, which is the significant problem at shielding depths typical of present manned spacecraft (for ISS about 20g/cm^2). HEDS mission scenarios generally assume "storm shelters" for SEPs and adequate warning from the Space Weather Program to utilize them. Some of the Active (Electromagnetic) concepts examined here have previously been proposed as shielding for

SEPs which have much softer spectra than GCRs. In this report we evaluate the ability of these concepts to protect against GCRs. Any shield protecting the crew from GCRs will be even more effective against SEPs.

For the discussions of this Workshop the participants were divided into three teams as indicated in the participant list (p. 11). The rationale for this was the commonality of the topics to be discussed, including the physical sciences involved, and the commonality of the discriminators ("figures of merit," dual uses, penalties, hazards, etc.). Five items on the Headquarters Working Group list were not listed for the teams. There were two "materials on Mars" concepts that were covered by previous studies for the Mars material option. A universal consensus seems to exist on the third item "Design Spacecraft According to Human Requirements." The fourth and fifth items, "place the spacecraft in a cloud of neutral gas or dust" and "a large sail/shield" (which fell in two concept categories) were evaluated separately.

After a half-day general discussion of the radiation problem and the objectives of the Workshop, the participants broke into their assigned teams. Most of the deliberations took place in three separate teams with two "midcourse" general discussion sessions. The teams were instructed to conclude their deliberations with the following products:

- A ranking of the concepts according to their utility for cosmic ray shielding, the perceived feasibility of development, foreseen hazards, engineering difficulties, etc.
- Identification of the concepts that have no merit for cosmic ray shielding, insurmountable physical or technical difficulties, or extreme hazards
- Recommendations for the next phase of research for those concepts which show promise for practical implementation
- An assessment sheet and a description for each concept
- A summary of team findings

In their deliberations each team consulted the published literature (copious for some topics, sparse for others). Consultants and experts both present at the Workshop and participating through teleconferences and e-mail, were utilized. For several topical areas (particularly in Extraterrestrial and Active [Electromagnetic] categories), specific calculations and analyses of data bases were performed. Most of these topics had been covered with discussions, literature search, calculations, and data base analyses before the meeting. These analyses are briefly described in Appendix B.

The pages that follow list the concepts organized by category, the team members, and the assessments of each concept.

Shielding Concepts Listed by Category

(Suggested Approach for Figures of Merit/Discriminators)

1. ***Active (Electromagnetic) Methods***

- Electric Fields
- Magnetic Fields (attached coils)
- Magnetic Fields (deployed large diameter coils or shields bearing magnets)
- Plasma Methods (expand magnetic field, produce electric field)

Common Elements:

- Many previous studies of physics for most; some studies of engineering
- Requires space power to develop fields; requires superconducting magnets
- To shield against GCRs one must have either very high fields or very extended fields
- $\left|\int_L \vec{B} X d\vec{l}\right|$ > 1000 gauss km or V > 10^{10} volts

Proposed Figures of Merit/Discriminators:

- $\left|\int_L \vec{B} X d\vec{l}\right|$ > 1000 gauss km or V > 10^{10} volts
- Smallest stored energies in field
- Minimized effects of fields on crew and equipment (< 2000 gauss)
- Perceived practicality
- Hazards

2. ***Extra-terrestrial Concepts***

- Comets
- Asteroids
- Earth-orbit Debris
- Martian Terrain/Regolith/Water
- Lunar Material

Common Elements:

- These are mass shielding ideas
- Transportation is a common element
- Attachment, drilling, processing, etc., are required
- No study yet as relates to cosmic ray shielding for comets, asteroids, debris

Proposed Figures of Merit/Discriminators:

- Availability of suitable objects (numbers, mass available, orbits)
- Transportation scenarios, number of stops (ΔV, etc.)
- Practical considerations (ease of attachment, drilling, etc.)
- Possible disruption of object, etc.
- Hazards

3. ***Novel Materials Concepts***

- Quasi-crystal Hydrogen Absorbers
- Palladium, Alloys as H Absorbers
- Carbon Nanomaterial Absorbers
- Solid H
- Metal Hydrides
- Borated CH_2 and Other Compounds

Common Elements:

- This is mass shielding
- Goal is lowest average atomic mass achievable (polyethylene, CH_2 is current "standard")
- Dual use would modify the lowest average atomic mass rule
- Neutron absorption
- Structural or other use
- Volumetric considerations

Proposed Figures of Merit/Discriminators:

- Average atomic mass number
- Mass fraction of hydrogen
- Dual use as construction material, neutron absorber, fuel, etc.
- Perceived practicality (fabrication, mechanical properties)
- Hazards

Participants/Teams

Active (Electromagnetic) Concepts

James H. Adams, Jr.	NASA/MSFC (Moderator)
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Robert Cassanova	NIAC
Dennis Gallagher	NASA/MSFC
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* Lawrence Townsend	University of Tennessee
* Hadley Cocks	Duke University
* Bruce Remington	Lawrence Livermore National Laboratory

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William Kinard	NASA LaRC
Keith Noll	Space Telescope Science Institute
Larry Kos	NASA/MSFC
*Kent Joosten	NASA/JSC

Novel Materials Concepts

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Richard Grugel	NASA/MSFC
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* Michael Heben	National Renewable Energy Laboratory
* Andy McClaine	Thermo Tech
* Bruce Remington's Group	Lawrence Livermore National Laboratory

* Not attending; Inputs and Reviews

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Dave Dooling	Infinity Technology
Dannah McCauley	UAH
Karen Murphy	Morgan Research Corp.

Summary of Concept Assessments/Recommendations

This section briefly summarizes the assessments of each concept considered. A rationale for each assessment is included in Appendix B.

Active (Electromagnetic) Concepts

l. Mini-Magnetosphere Plasma Propulsion (M2P2)

- Plasma expansion of field demonstrated in small-scale chamber
- Energy requirements seem modest
- Scaling to $\left|\int_{L} \vec{B} X d\vec{l}\right| > 1000$ gauss-km has not been calculated
- Concern about scaling, plasma instabilities and plasma loss
- Dual use for propulsion
- *Recommend a feasibility study including a thorough assessment of the shielding effectiveness by cosmic ray tracing calculations in the field.*

2. Magnetic Field Produced by Deployed Coil

- Published reports indicate SEP shielding with moderate field strength and stored energy
- The point dipole approximation implicit in the published SEP shielding calculations introduces large errors
- While a single coil must have too much stored energy, it may be possible to find a workable multi-coil configuration
- Very large magnet coils required (>10km) for GCR shielding
- Possible mechanical-magnetic field instabilities during deployment and charging
- *Recommend a search for multicoil configurations that will produce a large weak field.*

3. Electrostatic Field

- A positive potential of several billion volts is required, for GCR shielding
- The required potential is too large and space is too conductive for natural “spacecraft charging” concepts
- “Confined” electric fields appear to be the only feasible concept
- Large electrostatic generators would be required for confined electrostatic fields for GCR
- For GCR shielding very large structures (of order 20 km) would be required to prevent electrical breakdown
- *Not recommend for study*

4. Electric Field Produced by Plasma

- The concept must produce several billion volts for GCR shielding
- Electron plasma (accumulated electrons stored in a magnetic field) contains several Coulombs of electrical charge (typical of lightning bolt)
- Plasma instabilities, electron precipitation, etc. are highly probable
- The concept would require a huge vehicle
- Large electron accelerators are required to compensate for leakage
- *Not recommend for study*

5. Magnetic Field from Local (Spacecraft) Coils

- Very high magnetic fields are required and stored energies are equivalent to that from nuclear weapons detonations
- Large structural mass is required to support coils, exceeding the weight of direct mass-shielding
- Explosion and large electromagnetic pulse will occur if coil is breached, or superconducting magnet quenches (goes normal)
- *Not recommend for study*

6. Large Sail/Shield Concept

- Small magnets attached to a thin shield deployed upstream along the interplanetary magnetic field deflect solar energetic particles streaming along the field before they reach the spacecraft
- Not effective against galactic cosmic rays
- Solar energetic particle events have a broad angular distribution about the local magnetic field direction when streaming and usually become isotropic early in the event, defeating this shield concept
- *Not recommended for further study*

Extra-terrestrial Concepts

l. Use of Mars Surface/Subsurface Material on Arrival

- The radiation shielding using local materials for a Mars base has been covered in numerous preliminary studies (e.g., Workshop on Strategies -- Wilson, 1997)
- *Recommend continued studies -- this is definitely useful*

2. Areas on Martian Surface with Natural Atmospheric and Terrain Shielding

- Since the cosmic ray flux is isotropic to first order terrain, shielding should scale as the fraction of the celestial sphere that is visible from a surface location. This is modified by interactions of cosmic radiation in the atmosphere and Martian surface through cascading/ backscatter of the secondary particles.
- *This should be pursued with detailed calculations of the atmospheric and surface radiation environment and precursor measurements as suggested in Appendix A*

3. Orbiting Debris

- Adequate nonfunctional material exists in orbit; a number of 'stops' would be required to collect them
- Spent rockets and defunct spacecraft would require processing by methods that would not produce more small orbital debris
- Processing would probably need to be performed by separate robotics spacecraft
- Permission must be obtained from original owners
- Composition is uneven (aluminum structures, solar arrays, electronics modules, etc.), therefore shielding value is not homogenous
- Some components may be hazardous (residual propellant, NiCd batteries, pyrotechnics)
- *If a compelling case can be made for the need to remove these objects from space, consider investigating this method*

4. Use Lunar Regolith or Water-Ice

- Delta-V penalties for transit vehicle
- Requires processing of lunar material to produce useable shielding
- Robotic scenarios seem to be required
- *Not recommended for study except for Lunar Base habitat shielding*

5. Rendezvous with Asteroids and Burrow In

- Analyses of known asteroids show that appropriate candidates must be very rare. Furthermore, two are required (transit to and from Mars) for each method
- Large delta-V penalties for the current best candidate. This significantly extends the mission.
- Tunneling, mining, manufacturing operations required
- *Not recommended for study*

6. Rendezvous with a Comet and Burrow In

- Suitable comet trajectories are very rare; at present no viable candidates exist
- Very large delta-V penalties that prolong the mission
- Tunneling/mining/manufacturing operations are required
- Surrounding debris and volatile materials in core produce hazards
- *Not recommended for study*

7. Place Spacecraft Within a Cloud of Neutral Gas or Dust, Bound to the Spacecraft Electrostatically or Magnetically

- Effectively shielding against GCRs requires a thickness equivalent to tens of cm of condensed material
- The cloud would have very large dimensions compared to the transit vehicle. Thus, its mass would greatly exceed that required to locally shield the crew compartments.
- If the "neutral" cloud could be bound electromagnetically (by polarization or paramagnetic properties ?), it would be difficult to keep in place because of course correction burns. It might also be eroded by the solar wind.
- *Not recommended for study*

Novel Materials Concepts

l. Carbon Nano-materials

- Confirmed storage of H up to 6% mass fraction[1] and reports of up to 20%
- Large and active research base for hydrogen storage and materials applications
- Dual use as shielding and structure/H storage a possibility
- *Recommend continued research in this area and liaison with DOE studies*

2. Metal Hydrides

- Various metal hydrides contain 7-18% hydrogen
- LiH has been fabricated for space reactor shielding
- LiH is competitive with CH_2 in shielding cosmic rays
- $LiBH_4$ contains largest mass fraction of H (18%)
- Reactive to various degrees with air and water
- DOE is studying hydrides for hydrogen storage
- *Recommend studies of fabrication, encapsulation for hazard abatement, and liaison with DOE studies on these materials. Recommend assessment of relative shielding effectiveness using a code such as HZETRN.*

3. Palladium Alloys for Hydrogen Storage

- Higher volumetric density for hydrogen
- Mass fraction of hydrogen ~4% reported
- High average atomic mass; concern about neutron production
- May have dual use applications, particularly where volumetric considerations are important
- *Continue present studies and evaluate shielding effectiveness. Recommend assesment of relative shielding effectiveness using a code such as HZETRN.*

4. Polyethylene

- Polyethylene is best "standard or non-novel" material (except for H) since it contains 14% mass fraction of hydrogen and carbon preferentially fragments into 3xHe rather than neutrons
- In calculations using HZETRN, borated polyethylene is a slightly worse shield than pure polyethylene because B releases neutrons in interactions as well as absorbing them
- *Recommend investigation of possibility of laminates, etc., with pure polyethylene. Reevaluate borated polyethylene with future improved shielding codes for thicker shields.*

5. Quasi-crystals

- 1-2.5% mass fraction of absorbed hydrogen
- High atomic mass absorbers
- *Not competitive with other materials considered here as radiation shield, not recommended for further study*

[1]For reference polyethylene is 14% hydrogen by weight.

6. Solid Hydrogen

- Has been studied for propulsion (slush hydrogen)
- Not a rigid material, and density slightly less than liquid
- Costly
- *No apparent advantages over liquid H_2 for shielding, not recommended for study*

Design Spacecraft According to Human Requirements

The integration of radiation shielding considerations into the preliminary architecture design and systems engineering for interplanetary spacecraft has previously been advocated by many investigators associated with the HEDS radiation shielding issue (Wilson, 1999, 2000; Parnell, 1998). If this can be accomplished with an efficient process, it is more likely that deep space manned missions can meet crew radiation limits without adding excessive mass for radiation shielding or resorting to exotic strategies with their complications. Since accurate shielding calculations require accurate mass models, they are labor intensive to perform. This is because no satisfactory means exists to import 3-D computer-aided designs (CADs) into the radiation transport codes. The Workshop suggests NASA consider adopting 3-D CAD software that complies with the ISO 10303 standard entitled “Standard for the Exchange of Product Model Data” for the design of manned spacecraft. The Workshop also suggests the development of design rules requiring the use of “tags” to define the material content of each volume in the design. Finally, the Workshop suggests that a committee be formed to work out a plan for implementing these recommendations. Basic information about radiation shielding properties of materials, and geometrical considerations in “Rules of Thumb” form should be developed as guidance for all mission designers.

Appendix A

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Report of the Active (Electromagnetic) Concepts Panel

Active Radiation Shields

Concepts for active shields fall into four categories: electrostatic shields, plasma shields, confined magnetic shields and un-confined magnetic shields. Shields in these four categories are briefly described below. In addition to these brief descriptions, some concepts are discussed separately. These include the M2P2 concept and the large coil concept. As an aid to understanding the evaluations of the magnetic models, a note on magnetic models is attached at the end of this section. The ability of many of these active approaches to shield against galactic cosmic rays has been reviewed previously. The results of those reviews have been quoted here in the summary below and in two separate sections, one entitled "Pure Electrostatic Shielding" and the other entitled "Plasma Radiation Shield."

Electrostatic Shields

The idea is to use an electric field strong enough to repel the cosmic rays. Such a field must be of the order 10^{10} volts. This class of shields has been reviewed by Townsend (1983, 2000), Morozov *et al.* (1971), and Sussingham *et al.* (2000). All these authors dismiss this approach because of the large field required and the creation of intense secondary radiation within the shield due to various mechanisms. This is discussed in more detail in the section entitled "Pure Electrostatic Shielding" which follows.

Plasma Shields

There are several ideas to use plasma to create an electrostatic shield. Townsend (1983, 2000) and Sussingham *et al.* (2000) have examined these ideas and concluded that they should be ruled out both on account of the extremely high electrical potential required and because of the huge energies stored in magnetic fields in some concepts. One of these ideas, which used magnetically confined plasma to create an electrode, is discussed in detail in the section entitled "Plasma Radiation Shield" which follows.

Confined Magnetic Fields

The concept is to use magnetic fields to deflect the cosmic rays from the crew quarters of the vehicle. To avoid exposing the crew to an intense field, it is confined in a double-walled torus. This surrounds the crew with a "wall" of magnetic field that deflects the radiation. This approach was reviewed by Townsend (1983, 2000) and Sussingham *et al.* (2000) who found that the mass required for such a magnet greatly exceeded the mass of material shielding to achieve the same degree of protection.

Unconfined Magnetic Fields

The concept here is also to deflect the cosmic rays with the magnetic field, but in this case the field is allowed to become very large. Early concepts were based on placing coils in the vehicle because liquid helium would be required to cool the superconductors considered. These designs were more massive than the material shielding needed to provide the same protection. In addition they posed two hazards: (1) the magnetic field in the crew quarters was unacceptably high and (2) the stored energy in the coil was so large that an unplanned quench of the superconductor would have been catastrophic. Still, Townsend (2000) did not rule out unconfined fields noting that the Earth's field provides protection safely at field strengths of ≤ 0.5 gauss. The Workshop reviewed three concepts for un-confined field shields. One of these concepts uses a very large coil of high Tc superconductor deployed beyond the vehicle. Sussingham *et al*. (2000) reviewed the concept favorably. The second relies on inflating the field with plasma to obtain a large field structure. The last proposes to deploy a large sail/shield far upstream along the local interplanetary magnetic field to deflect solar energetic particles. These are discussed in more detail in the following pages.

Magnetic Shielding using a Large Coil

The Concept

It has been suggested by Cocks (1991) and Cocks *et al.* (1997) that magnetic shielding could be obtained by deploying a large circular loop of high-temperature superconducting wire far beyond the manned vehicle. The idea is to make use of the large size to reduce the stored energy in the coil needed to provide the magnetic shield. Zubrin and Martin (2000) have also investigated such a loop to be used as a large magnetic sail. Their report includes many details concerning the deployment of such a wire loop.

The Shielding Effectiveness

The idea was suggested as a shield against solar energetic particles. Cocks (1991) and Cocks *et al.* (1997) use Stormer theory to estimate the magnetic moment needed to provide the required shielding. Stormer's equation uses the point dipole approximation for the magnetic field. It's use for the large dipole proposed by these authors appears to be incorrect. We have recalculated the magnetic shielding effectiveness of their proposed coil using the Law of Biot and Savant to obtain the field near the coil. The resulting field can be described using a spherical harmonic expansion (Jackson, 1962).

To obtain a measure of the shielding effectiveness of the coil, we used the method for "other fields" in the "Notes on Magnet Models" below where the reference value of 960 Kilogauss.meters was obtained for the line integral in the magnetic equatorial plane.

We used the spherical harmonic field model discussed above to carry out a line integral in the dipole's equatorial plane from infinity to 5 meters from the wire. The current in the wire was adjusted to obtain a value of 960 Kilogauss.meters for this integral. To obtain this integral value required a current of $1.05\text{X}10^{8}$ Amperes. Using Wheeler's approximation for the inductance of a single wire loop,

$$L = R\mu_0[\ln(8R/a)-1.75) = 0.224 \text{ Henrys.} \qquad (1)$$

where $M_0 = 4\pi\text{X}10^{-7}$, the coil radius, R = 10 km and the wire diameter, a, is 0.25 mm. We calculate the stored energy in the loop to be,

$$E = 0.5Li^2 = 1\text{X}10^{15} \text{ Joules; or 240 Kilo-tons of TNT} \qquad (2)$$

(more than 10 times the Hiroshima bomb)

This is quite different from the result obtained by Stormer theory.

Deployment

The concept for deploying the wire is to unfurl it and use current flowing in the wire to cause it to circularize.

The stored energy, E, in the wire depends on its inductance, L, and the current, i, flowing in it according to the equation (2), where the inductance is given by (1). Using these equations it is easily shown that a single large circular loop has less stored energy than any other configuration that the wire might assume. It can therefore be expected that the loop, once energized, will form the desired circle.

The problem is that the loop will be too warm to be superconducting until it is properly deployed. This makes it necessary to consider a wire that is composed of a low resistance room temperature conductor with superconducting strands imbedded in it. The room temperature conductor might be silver, copper or aluminum. The idea is to pass a small current though the deployed loop to cause it to circularize. Zubrin and Martin (2000) have considered this problem. Considering only the acceleration obtained from the current, they estimate that it would take 23 days for the coil to become circular. This is likely to be an underestimate because once the coil reaches its full size, it is likely to oscillate about the final circular configuration for some time.

Cooling the Wire

The high temperature superconductor which looks most promising for this application is barium strontium copper calcium oxide (BSCCO). The superconducting transition temperature for this alloy is 90°K, but to carry the required current it must be operated at 60°K. The plan is to insulate the sunward side of the coil and cool it by radiating heat to deep space from the shadowed side. This is technically feasible using well-understood techniques of multi-layer insulation and radiative cooling. The problem is to orient the coil so that the insulated side is facing the sun everywhere around the coil. Any torsion in the wire could cause some portion of it to stabilize with the insulated side pointing incorrectly.

Perhaps the authors might overcome this difficulty by deploying a pair of coils with separators located between them periodically. The minimum energy configuration for the pair of coils will be one in which their radii are equal. This will force the two wires to take the same orientation everywhere around the loop, making it possible to orient the insulation toward the sun everywhere. Nevertheless, because the coil will probably oscillate both radially and torsionally it may be a long time before the wires will cool to 60°K around their entire circumference.

The assessment of the Workshop is that this idea is impractical. Nevertheless, if magnetic shielding can be made to work, it must be through the use of a very large weak field. It may be possible to find a multicoil configuration that will produce the required large weak field.

Mini-Magnetospheric Plasma Propulsion as a Means for Cosmic Ray Shielding

Objectives

Mini-Magnetospheric Plasma Propulsion (M2P2) seeks the creation of a magnetic wall or bubble (i.e. a mini-magnetosphere) attached to a spacecraft that will deflect charged particles that make up the solar wind and cosmic rays. The mini-magnetosphere uses the injection of low energy plasma to inflate the magnetic field over substantially larger distances than a simple dipole field pattern would give. Thus, M2P2 has the advantage that it eliminates the need for previously proposed very intense magnets and the concomitant high energy storage requirements needed for local magnetic shielding, as well as eliminating the need for the deployment of large scale (>1 km) current loops in space proposed for magsail-type shielding (Zubrin, 1993). Small units which would consist of magnets with strengths of a few kilogauss, and plasma source weighing a few tens of kg with a power consumption of about 1 kW and a mass consumption of about 0.25 to 1 kg/day. A set of four such units could potentially provide about 100 kGauss meters of shielding which would effectively stop SEP particles. M2P2 has another advantageous feature because it has economies of scale in that convection losses from the mini-magnetosphere decrease with increasing size as surface to volume ratio falls. As a result, a 1000 kGauss meter shield (i.e. deflecting GCR particles) is potentially possible with existing technology without the need for a large mass or power requirement. The shielding could be used for long duration spacecraft missions, such as return trips to Mars or Jupiter, and provide not only shielding for the spacecraft but extremely efficient propulsion for the spacecraft. In addition, it could provide a large-scale (tens of square km) radiation shield on solar system bodies where there is little or no atmosphere (i.e., moons of planets and asteroids). Such large scale shielding would allow long duration human exploration without the need for the astronaut to carry bulky personalized shielding.

Current Research on the M2P2

Research for the modeling and the development of the M2P2 is supported by a Phase Il grant from NASA's Institute for Advanced Concepts (NIAC). Large scale testing of the M2P2 prototype is being done in a collaboration between the University of Washington and NASA Marshall Space Flight Center.

Dynamics of the M2P2

M2P2 seeks to create the mini-magnetosphere in much the same way as nature generates coronal mass ejections and the enlarged Jovian magnetosphere (Winglee *et al*., 2000a,b). In the latter two cases, plasma is created on closed magnetic field surfaces. When the plasma reaches sufficient pressure to overcome the magnetic field tension, the magnetic field expands to scale sizes very much larger than the original object. The laboratory prototype of the M2P2 uses a plasma source embedded asymmetrically in a dipole-like magnetic field. Breakdown of the plasma can be produced at neutral pressures of between about 0.25 to 1 mTorr to produce plasma densities of the order of 10^11 - 10^12 cm-3 with a temperature of a few eV. The plasma pressure is sufficient to overcome a magnetic field of several hundred to a thousand gauss and cause the field's outward expansion or inflation into the mini-magnetosphere. The motion of both open and closed field lines within the vacuum chamber is demonstrated through the optical emissions from the helicon plasma.

A joint collaboration between the University of Washington and NASA MSFC has demonstrated inflation of the magnetosphere to at least several feet away from the magnet. The experiment shows plasma flows all the way to the chamber walls at a distance of 16 feet but the determination of closed/open field structures at these distances is very difficult. In space, inflation to about 15-20 km would be expected for the same configuration, and would produce a force of about 1-3 newtons for the expenditure of about 1 kW of power, and about 0.25 to 1 kg/day of gas.

Computer simulations of the expected magnetic field for a single unit and a multiple (four unit) system have been undertaken. These results indicate that the main source of loss from the minimagnetosphere is through convection of plasma and magnetic field around the flanks of the magnetosphere. Because the surface-to-volume ratio is smaller for the multiple unit system, losses are reduced and the resulting mini-magnetosphere is actually more than four times larger than the one obtained with a single unit. Thus, the M2P2 system has the favorable feature that scaling to a larger system is more efficient, and more easily deployed.

The present simulations indicate that the 4-unit system could potentially produce a magnetic field structure such that, in almost all directions, the integrated field strength a cosmic ray would encounter would be approximately 100 gauss km. Further research is needed to verify the scaling. Finally, single particle trajectories need to be traced through the field to fully prove the M2P2's shielding capabilities.

The computer simulations of the mini-magnetosphere also show the interesting feature that the formation of the tail current sheet is suppressed by the injection of plasma on the front side that drives the inflation of the mini-magnetosphere. This feature, plus the scale size of the minimagnetosphere, have the property that the formation of ring currents and radiation belts (as occur in the terrestrial magnetosphere) may be suppressed for ions. Further research is needed to determine the orbits of trapped electrons.

Pure Electrostatic Shielding

There are two forms of pure electrostatic shielding, and neither is sound. In one scheme, the space vehicle is pictured as being constructed of two concentric shells, and these shells act as a charged capacitor. In this arrangement the space vehicle as a whole is electrically neutral. To be effective against galactic cosmic rays, the potential between the shells would have to be about 10^{10} V. The largest steady voltages produced on Earth between conductors are found in Van der Graaff machines. Despite the massiveness of these machines, they cannot attain voltages higher than 20 MV.

Experience with space-borne electrostatic analyzers indicates that electric fields stronger than $2X10^6$ V/m between conductors are likely to breakdown. If a is the radius of the inner shell and b is the radius of the outer shell, then the stored charge on the shells is

$$Q = 4\pi\varepsilon_0 V[ab/(b-a)],$$

and the electric field is,

$$E = Q/(4\pi\varepsilon_0 r^2)$$

Where V is the voltage, r is a radial distance between a and b and ε_0 is the permittivity of free space (= $8.85X10^{-12}$ F/m). Taking a = 10,000 meters and solving for the outer shield radius, we get b = 20,000 meters and Q = 22,000 Coulombs. The stored energy in the shield would be E = 0.5QV = $1.1X10^{14}$ Joules (equivalent to 26 kilotons of TNT). The force between the shells is F = 0.5QV/(b-a) = $1.1X10^{10}$ Newtons (or 1 million metric tons of force).

This is obviously unrealistic.

In the other arrangement, the space vehicle is considered as a charged conductor at 10^{10} V relative to "infinity."

The difficulty with the second scheme is, perhaps, slightly less obvious. It might be thought in the first instance that the very high vacuum prevailing in deep space would itself be a very good insulator. This is not the case, however, since the solar wind fills the planetary system with free protons, and electrons to a density of about 10/cc. These charges are free to respond to any potential of either sign. If one tried to maintain the space vehicle positive as a protection against energetic protons, free electrons in space would discharge the potential in a time so short that the scheme becomes quite unrealistic.

Plasma Radiation Shield

This section reviews concepts by Richard H. Levy and others reported in: "STUDY OF PLASMA RADIATION SHIELDING FINAL REPORT" prepared by AVCO-Everett Research Laboratory, a division of AVCO Corporation, Everett, Massachusetts, Contract NAS 8-20310, May 1968, for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center. The following description was abstracted from that report. Note that this concept was to shield against solar particle events. The potentials, energies, and charges in the concept must be scaled up by more than two orders of magnitude to be effective against galactic cosmic rays.

Definition

The Plasma Radiation Shield is an active device using free electrons, electric and magnetic fields for the purpose of shielding astronauts from energetic solar flare-produced protons. The specific purposes of the two fields are as follows: the electric field is the direct means of providing the shielding against energetic protons, while the magnetic field has the sole purpose of supporting the electric field by trapping electrons at a separation from the spacecraft. It follows that the electric field that is required for the Plasma Radiation Shield is just the same, as that required for the pure electrostatic shield. We therefore require the establishment of a voltage on the order of 30-100 MV.

Electrostatics

Consider a conducting sphere of radius a carrying a positive charge Q on its surface; the electric field produced by this arrangement (in the absence of other charges) is radically outwards from the surface of the sphere. The magnitude of this radial electric field at radius $r(>\rho)$ is given by

$$E = Q/4\pi\varepsilon_0 r^2 \tag{1}$$

This field can be derived from a potential, Φ. In defining the potential an arbitrary constant may always be added; in this case we have assumed that $\Phi = 0$ at a large distance from the sphere. It follows that the sphere is at a potential

$$\Phi(\rho) = Q/4\pi\varepsilon_0 \rho \tag{2}$$

above the potential of distant space.

A way of interpreting this statement in terms relevant to the Plasma Radiation Shield is as follows: the work necessary to bring a proton (of charge + e) from infinity to the surface of our sphere is just $e\Phi(\rho) = eQ/4\pi\varepsilon_0\rho$. In space the only source of this energy is the kinetic energy of the proton when at infinity; only if this exceeds the quantity $e\Phi(\rho)$ will the proton be able to reach the surface of the sphere. Measuring this kinetic energy in electron volts we find (since the charges on an electron and a proton are of equal magnitude) that the sphere is electrostatically shielded against protons having less than $\Phi(\rho)$ electron volts. If we wish to exclude protons up to 50MeV, $\Phi(\rho)$ must have the value 5×10^7 volts. For a capacitor of capacitance C, the charge and the voltage are related by the formula

$$Q = C\Phi$$

Comparing this with the formula (2) we see that the capacitance of the isolated sphere is

$$C = 4\pi\varepsilon_0\rho$$

Thus, a two-meter radius isolated sphere has the capacitance 222×10^{-12} farads. It follows that if we wish $\Phi(\rho)$ to be 5×10^7 volts, the charge Q must be 11.1×10^{-3} coulombs.

The arrangement described is not, as it stands, satisfactory. This is because a positive charge of the magnitude being considered would attract electrons from the surrounding space plasma at a rate so large as to make the whole concept useless. In the Plasma Radiation Shield, a cloud of free electrons surrounds the vehicle, the cloud being held in place by a magnetic field. Now the voltage across the electron cloud is always fixed by shielding considerations, but the details of the way in which the electron cloud is distributed are quite difficult to calculate. However, any given distribution can be characterized by a capacitance C.

Magnetic Field

To confine the electron cloud around the vehicle with a magnetic field, the field lines must surround the vehicle without ever leading to it. This configuration can be realized if the vehicle is in the shape of a torus (or doughnut) and an electric current is made to circulate around the torus. The magnetic field lines will then surround the torus forming a dipole field configuration. This field confines the electron cloud. The force exerted on an electron of charge -e moving with velocity v in a magnetic field **B** is -e(**v x B**) . This force is perpendicular to both **B** and **v**. This force binds each electron to a field line. The electrons gyrate around these field lines, spiraling along the lines as they circulate around the vehicle.

A second observation of considerable importance also follows directly from the form of the expression (**v x B**) for the force exerted on an electron by a magnetic field. The electron cloud must be permanently in motion to remain confined by the field. The effect of the electric field is to cause the electrons to drift around the torus with a velocity given by $(\mathbf{E} \times \mathbf{B})/B^2$ (Rietz and Milford, 1962). It does not cause electrons to precipitate onto the vehicle.

Containment of the Electron Cloud

The authors of this concept expressed concern that the electron cloud would not remain stable for long periods of time. The authors speculate about several effects that could cause radial diffusion of the electrons or instabilities in the electron plasma.

Summary

This concept even for protection against solar energetic particles is flawed. The solar energetic particle flux contains electrons as well as protons. The electron flux can be 10% of the proton flux at the same energy. The shield energizes these electrons making them more of a hazard. This will at least partially offset the value of the shield.

To be useful any shield concept must also shield against galactic cosmic rays. This concept must be scaled up from value 5 x 10^7 volts to value 1 x 10^{10} volts to be effective against galactic cosmic rays. It must also be in place continuously. This greatly increases the concerns about radial diffusion or plasma instabilities causing the shield to be lost.

From the preceding discussion of the purely electrostatic shield, it is clear that the electron cloud would have to be located 5 km from the vehicle. Because the vehicle is a torus, its dimensions would have to be much larger, perhaps 20 km in diameter.

The field 5 km from the vehicle would have to be several kilo-gauss to contain the electron cloud. This requires a huge magnetic field. This field may be large enough to provide the required shielding by magnetic deflection without the need for the electron cloud. In any case, the energy stored in the magnetic field would probably be a hazard. Such magnetic shield concepts are discussed elsewhere in this report.

Large Sail/Shield Concept

This was suggested as a concept for shielding against solar energetic particles. The idea is to take advantage of the fact that solar energetic particles (SEPs) steam along the interplanetary magnetic field lines connecting the spacecraft to the SEP source near the sun. A thin shield, like a solar sail, provides the protection. This shield would contain tiny magnets and scattering nuclei. It would be placed far upstream of the spacecraft to deflect the particles.

First, as was shown in the introduction, it is crucial that the shield also protect against galactic cosmic rays to be useful. Galactic cosmic rays are isotropic. The shield will not even provide protection from those arriving from the shielded direction since it will scatter as many cosmic rays into the solid angle subtended by the spacecraft as it will scatter out.

In the case of solar energetic particles, the shield causes a beam of particles to diverge, thus reducing the flux at the spacecraft. The available data on anisotropies in SEP events have been recently reviewed by Tylka (2000a). He shows that large SEPs become isotropic early in the development of the events, well before the maximum intensity is reached and long before half of the total fluence is integrated. Small events do show some anisotropy during the first half of the event. Reames (2000) shows data from such a small event recorded by the EPACT instrument on the Wind spacecraft. Even during the anisotropic part of the event, the arrival directions are broadly spread about the local magnetic field direction with the half-intensity point at approximately 70° to the local magnetic field direction. Such a broad angular distribution largely defeats the idea of a thin shield far upstream because now the shield would have to subtend a large solid angle with respect to the spacecraft and would be less effective since the particles scattered away from impact with the spacecraft would now be partially compensated by ones scattered toward the spacecraft. Furthermore, the shield would be completely ineffective against the large event since they become isotropic early in their development.

The available data are primarily from lower energy SEP particles. The anisotropy of the higher energy particles that pose the hazard have not been investigated. The physical processes that cause the large events to become isotropic early (proton-generated waves that reduce the scattering mean free path by orders of magnitude), should still operate at higher energies however it can be quantitatively different. Tylka (2000b) points out that the most intense events are those for which the shock crosses the position of the spacecraft, increasing the intensity of the event by a large factor during the shock passage. During the most intense part of these events, when the spacecraft is within the shock, the particle will certainly arrive isotropically.

In summary, this concept does nothing to shield against galactic cosmic rays. Even if it were effective against SEPs, it would have to be augmented with a galactic cosmic ray shield. Any shield that is effective against galactic cosmic rays will be even more effective against SEP particles, rendering the proposed concept redundant. Secondly, it is highly likely that the proposed concept would not be effective against SEPs either because the particles do not stream in a narrow beam along the interplanetary magnetic field direction. Furthermore the large events probably deliver most of the fluence to the spacecraft after becoming isotropic.

This concept is not recommended for further study.

Notes on Magnet Models

Point Dipole Fields

For positively charged particles in the distant field of a dipole, the geomagnetic cutoff is given by Stormer's equation,

$$P = [3X10^{-4}\mu/r^2][(1-(1-\cos(\gamma)\cos^2(\lambda))^{1/2}/(\cos(\gamma)\cos(\lambda))]^2$$

Where P is the cutoff magnetic rigidity in GV, μ is the magnetic moment in m^2A, r is the distance from the center of the dipole in cm, γ angle between the particle's trajectory and magnetic west and λ is the magnetic latitude.

Note that the cutoff depends on magnetic latitude and the arrival direction of the particle. For latitudes near 90 degrees the cutoff is near zero. So dipole fields protect best for particles arriving in the magnetic equatorial plane and least for particles arriving from the polar directions.

At the dipole equator, this equation simplifies to $P = [3X10^{-4}\mu/r^2]$. The radius corresponding of a cutoff rigidity, P, is

$$r = (3X10^{-4}\mu/P)^{1/2}$$

This is called Stormer's radius. It is a measure of magnetic shielding effectiveness.

Other Fields

In principle one may be able to find a Stormer-like solution for the cutoff in field configurations other than a dipole but for the purposes of defining a figure of merit for the field, we recommend using the line integral of $\left|\int_L \vec{B}Xd\vec{l}\right|$ along the path of the particle as it approaches the center of the field.

It should be noted that for each pathlength segment, dl, the angular deflection (in radians) = $3X10^4 * \left|\int_L \vec{B}Xd\vec{l}\right|$ /P where B is in kilogauss, l is in cm and P is in GV. If the particle comes in from infinity and crosses perpendicular to the field, it will be deflected 90 degrees at its point of deepest penetration.

We have carried out the integral numerically in a model of the Earth's field to discover a reference value for this line integral. We integrated along the radius vector at -15 degrees latitude and +110 degrees east longitude down to the earth's surface. It is known (e.g., Shea, Smart, and McCracken, 1965) that the geomagnetic cutoff at this location is about 15 GV. We got a value of 960 Kilogauss.meters. Since we integrated radially and not along the cosmic ray's path, it is a bit of an under estimate (near cutoff cosmic rays spiral along the field until they mirror and leave), but it is close.

For non-gaussian fields we suggest using the criteria:

$$\left| \int_L \vec{B} X d\vec{l} \right| > 960 \text{ Kilogauss.meters}$$

<u>Limits on Exposure to Static Magnetic Fields</u>

There are no statutory limits in the U.S. The International Commission on Non-Ionizing Radiation Protection recommends an occupational limit of 2 kilo-gauss.

Report of the Extra-terrestrial Concepts Panel

Extra-terrestrial materials could be used for shielding astronauts from cosmic radiation on missions to Mars. We have identified four general sources of material: lunar regolith, comets, asteroids, and man-made orbital debris. Added equipment will be needed with all four sources for processing the material into a useful shield. Added propulsion is also needed for all four options — the spacecraft is required to visit other objects before, during or after its trip to Mars. Each source of material also has its own drawbacks and advantages that will impact the cost and safety of these missions. We examine the details for each of these sources below.

Lunar Regolith

Lunar regolith – rock and dust from the lunar surface – has been examined as a source of shielding for astronauts on the lunar surface. A few meters of this material can effectively shield lunar explorers for extended periods of time. If this material is to be used as a radiation shield on a Mars Mission habitat module it must be combined with a binder such as epoxy to form shielding units and then transported from the lunar surface to the Mars Mission spacecraft. The mass of material required for an effective shield is quite large. A shield consisting of 20 g/cm^2 of lunar regolith surrounding a habitat module 8 m in diameter and 8 m long would require 40 metric tons of material but only reduce the normally incident radiation by a factor of 2 (Simonsen, 1997). Such shielding would be inferior to more ideal shielding materials (polyethylene, water, or other hydrogenated materials) and be more massive as well. While lifting this material from the lunar surface may be more economical than lifting it from Earth, the penalties incurred by producing a massive shield that must be transported to and from Mars would seem prohibitive. Nominally, each metric ton of material added to the habitat module requires two metric tons of additional fuel to get it to and from Mars for a high performance (Isp = 940 sec) transportation system.

Lighter shielding material manufactured and transported from Earth will almost certainly be more effective and more economical in terms of both cost and energy.

Comets

The nuclei of comets would provide effective shielding due to the shear mass involved. A Mars Mission spacecraft might rendezvous with a comet in a suitable orbit and use the icy material for shielding. Some engineering and materials processing would be required to produce an effective shield. The comet body itself would block half of the incident galactic cosmic rays but additional shielding would require burrowing into the object or processing material into a shielding blanket surrounding the human habitat. With this scenario it is possible to get a large amount of mass shielding without the energy cost of launching the mass or propelling it into a planet-crossing orbit. Water from the comet is also a potentially valuable resource.

Approach, landing, and burrowing in a comet is technically feasible, but presents enormous engineering challenges, particularly for manned flight. Among the most serious challenges are the complex and unpredictable dust environment near an active comet nucleus, the unknown density, porosity, and material strength of cometary surfaces, and the lack of comets on orbits with practical combinations of perihelion, aphelion, and inclination (Harvard/CFA web site http://cfa-www.harvard.edu/iau/Ephemerides/Comets/). Dust leaving a comet is accelerated near the surface to a velocity of order 1 km/s. Spacecraft would need to be shielded against impacts with both microscopic dust and macroscopic fragments flowing out from the surface. Cometary activity is seen in objects even at large heliocentric distances (e.g. 2060 Chiron at ~10 AU). This activity is episodic and unpredictable. Landing near a latent site of activity or burrowing into a high-pressure pocket of trapped volatiles could prove catastrophic to a mission. The unknown, unpredictable environmental hazards would jeopardize the safety of astronauts. Our search for comets with suitable orbits did not yield a single candidate. We expect that comets with suitable orbits are very rare to non-existent.

Asteroids

Asteroids could be used for shielding in much the same ways as suggested for comets. Asteroids have several advantages over comets. The environment surrounding an asteroid is not as volatile or dangerous as that surrounding a comet. Asteroids with suitable orbits are also far more likely to be found. Using asteroids for shielding does share some of the same caveats associated with using comets or any other extra-terrestrial source – mining and/or materials processing equipment must be carried on the mission to produce the shield or shielding cavity. To be useful an asteroid must pass sufficiently close to both Earth and Mars on the same outbound orbit, while another, different asteroid would have to be utilized for the return to Earth.

Currently over 1000 asteroids are known to have orbits that bring them near Earth and possibly Mars (Marsden, 2000). For the larger asteroids with diameters greater than 5 km this list is probably close to complete (Rabinowitz *et al*., 1995). For smaller asteroids with diameters greater than 1 km it probably contains somewhat less than half of the true population. The smallest useful asteroids will have diameters greater than about 100 m. This list of known Earth Crossing Asteroids probably contains about 1% of these small asteroids. We have plotted orbits and calculated the positions of each of these asteroids, Earth, and Mars 40 years into the future. From this list of 1015 we find 63 asteroids with relatively close (less than 20 million miles) encounters with both Earth and Mars on the same orbital leg. However, the vast majority of these objects have relative velocities at these encounters that require prohibitive expenditures of energy. Limiting this search to asteroids with small relative velocities at the Earth and Mars encounters (comparable to those needed for the nominal mission without the asteroid encounter) yields only two candidates in the next 40 years and both provide only a return trip from Mars. A mission calculation using the best candidate (1999 JU3) requires 181 days just to rendezvous with the asteroid. The nominal return mission without the asteroid only takes 180 days total and requires less fuel.

We can imagine an "ideal" asteroid on an orbit that matches a nominal Mars mission transfer orbit. However, since two asteroids are needed for each mission (one for the trip to Mars and another for the return), we expect that the probability of finding a suitable set of these asteroids is extremely small. We also expect that the penalties in time and energy associated with the rendezvous with the asteroid and then the planets themselves will also make this alternative untenable. Nonetheless, as more of these objects are discovered it will be useful to examine their orbits to determine whether or not they might be used as resources on future missions.

Orbital Debris

Another possible technique for protecting a manned Mars mission is shielding it in a sheath composed of some of the man-made debris that has accumulated in geocentric orbit since the "space age" began in 1957. Of all the mass launched into orbit, the majority is still there and will remain there for many years. Only debris with an orbital altitude less than 400-500 kilometers is cleaned out by the process of energy reduction by atmospheric drag; above this regime, orbital debris stays indefinitely unless deorbited by a propulsion system. This debris comes from a variety of sources, and is of a variety of sizes, ranging from sub-micron to expended rocket bodies with masses of hundreds of kilograms. This population is logically divided into two parts; the population less than 1 centimeter in size, which must be treated by statistical techniques and by *in-situ* sampling, and that of a size greater than about 20 centimeters (about 1 meter at geostationary altitude). This latter population is tracked (and each object uniquely identified) by the US military and orbits are made available to NASA and the public. The latter population is discussed here. The smaller debris is expected to be in generally similar orbital regimes. However, given the large total mass requirements of radiation shielding, and the broad dispersal of particles, it seems implausible that enough of the smaller can be accumulated to provide a significant amelioration.

Approximately 8000 trackable objects are in orbit at any given time. Of all these objects, only about 5%, or less than 500, are currently active or useful payloads. The rest include nonfunctioning payloads, rocket bodies, and fragmentation debris. These are at a variety of altitudes and in a variety of inclinations. After a breakup or other debris-producing event, the east-west distribution of the pieces tends to spread out. However, the inclination stays essentially constant, and the apogee and perigee remain constant for orbits unaffected by atmospheric drag. The largest part of the object count is at varying altitudes from 300 to 1000 km. There is a significant component at 1500 km, above the radiation belts, and of course a significant population at geosynchronous altitude. The largest single population is found at an inclination near 63 degrees. This is the critical inclination of no perigee rotation into which many satellites are launched. There are also significant peaks at sun-synchronous altitudes of 80 and 100 degrees, and a population near the latitude of every major launch site.

There are three significant problems to space debris capture. Finding it is **not** a problem for this instance, since all large pieces are well tracked (http://www.spacecom.mil/factsheetshtml/reentryassessment.htm; http://science.nasa.gov/Realtime/JTrack/). There is some exception to this at geosynchronous altitude, where tracking is more difficult and non-functional objects are occasionally lost for a while because of lack of tasking. The first real problem is matching velocity and position with the object well enough to capture it. The velocity match is necessary because the possible delta V of up to 15 km/s is far too large for nondestructive capture. This requires a maneuvering capability. The energy required depends strongly on the type of orbit alteration required. Changing inclination is tremendously expensive in energy. Changing inclination by 90 degrees requires as much energy as the initial launch. Changing altitude by a significant amount is less expensive in energy. The most economical strategy is changing position in an east-west direction. This can be easily accomplished at any altitude; a small along-track thrust will change the orbital period, which will cause the orbit to precess in an east-west direction. Thus, any debris collection campaign should be preceded by a specific analysis of the objects to be accumulated to guide the collection. The debris collection scenario is well suited to a low thrust ion engine, but significant time will be required for multiple rendezvous. Thus, the concept of a precursor garbage collector satellite would probably be required.

When position and velocity are matched adequately, the debris must then be captured. Various techniques could be used; perhaps the best is a "butterfly net" strategy. Note that some kind of local maneuvering system must be in place to accomplish this, as adequate accuracy cannot be obtained by ground tracking.

After capturing, the debris must be formed to shield the habitat module. There are various possibilities here. It could be lashed in place, in a `hermit crab' strategy but it is questionable whether or not such an assemblage could survive the rigors of subsequent orbital maneuvers to get to and from Mars. It may be more desirable to form it into an ordered sheathing material. This would require some sort of crushing or forming machine in place. A central driver in this is the total thickness of shielding that must be in place. If the total thickness of aluminum or equivalent in the shield is 25 centimeters this represents some 150 metric tons, a significant fraction of the total debris mass. It also requires matching velocities with a number of large objects.

Finally, permission must be obtained from satellite owners since, under the Convention on Registration of Objects Launched into Outer Space of 1974, they retain title and liability even though a craft is defunct.

As with some of the other extra-terrestrial materials, the use of in-place space debris to shield a manned Mars Mission is certainly possible. It will require planning in any event, and its practicality is better for a shielding layer that is reasonably thin. As with the other concepts employing extra-terrestrial material, it requires manufacturing and/or materials processing equipment and could require significant amounts of fuel to maneuver between objects. One potential hazard with orbital debris may be the volatility of the debris itself (unspent fuel, etc.).

<u>Conclusions</u>

Examination shows that all these extra-terrestrial sources for shielding have significant problems. Lunar regolith can be disregarded due to the energy requirements associated with landing and lifting a substantial amount of material on and off of the lunar surface. Comet nuclei for shielding can be excluded due to safety concerns associated with the volatile environment and the energy and time required for such rendezvous. Asteroids provide more benign environments and may populate orbits that could be useful on such missions. However, we expect that the probability for finding a sufficient number of candidate objects is very small and that the penalties of energy and time associated with the asteroid rendezvous will make this option unattractive. Nonetheless, we should continue to examine the orbits of newly discovered asteroids to determine their utility for these missions. Orbital debris consisting of small objects will be difficult to accumulate and assemble into a useful shield. Larger pieces of orbital debris might be used, requiring fewer captures, but the acquisition of sufficient material and its assembly into a space-worthy shield will be difficult at best. This option might become more attractive if a "space garbage collector" was already deployed to clean up the orbital debris.

Report of the Novel Materials Concepts Panel

The objective set before the Materials Group of the HEDS Radiation Shielding Workshop was to review the potential efficiency of several novel materials or combinations of materials for shielding of human crew during a Mars expedition. Our purpose was neither to recommend a particular shielding material, nor to provide a definitive analysis of the claims made of certain new materials.

The radiation field with which we are primarily concerned is that of the galactic cosmic rays (GCRs), though there is also concern with intense, but short duration, fluxes associated with solar eruptions. In both cases the radiation of concern is relativistic atomic nuclei, composed of elements ranging in atomic number from hydrogen to iron. As many authors have pointed out, the most effective material per unit mass of shield is provided by hydrogen. Shields of heavier elements, lead for example, while commonly used for x- or γ-ray absorption, are much less efficient per unit mass than lighter elements for absorbing energetic nuclear particles. Indeed, detailed transport calculations show clearly that these heavy target nuclei are inefficient not only because of their lower cross-sections per g/cm^2, but also because they serve as the sources of dose-producing secondary particles such as short-range heavy nuclear fragments and penetrating neutrons. These effects may only be quantitatively assessed by a radiation transport calculation (Wilson, *et al.,* 1995, 1997, 1998). The results of two such calculations for several shielding materials in the GCR environment are shown in figure 1 (same as figure 5 on page 6), and figure 2 (Simonsen, 1997; Wilson, *et al.,* 1995; Wilson, *et al.,* 1997 — NASA CP-3360). These figures clearly show the monotonic increase in shielding efficiency as the mean atomic weight of the shield material decreases. They also show the non-intuitive (to those familiar with the exponential absorption law) result that 20g cm^{-2} of lead shielding against the GCR provides no reduction at all in tissue dose, while the same mass of hydrogen reduces the dose to a small fraction of the unshielded case. The curves also clearly show the relative inefficiency of aluminum as a shielding material when compared to O, C and H, i.e., elements that are present in water and polyethylene.

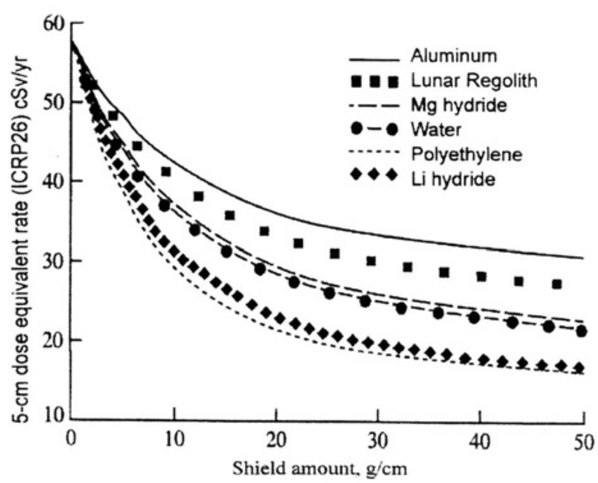

Figure 1. 5-cm depth dose for GCR at solar minimum as a function of areal density for various materials.

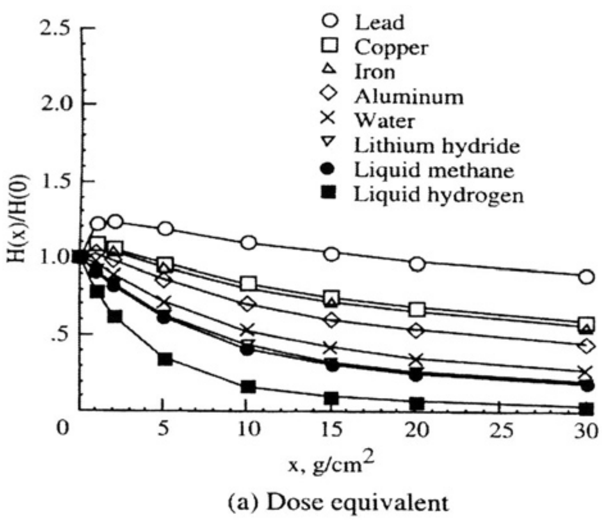

Figure 2. Relative attenuation of dose equivalent as a function of shielding depth (in terms of areal density, g/cm^2). (Wilson *et al.,* 1997, 1995*)*

The materials we have considered for shielding against GCRs are:

- Carbon nano-materials with absorbed H
- Metal hydrides: LiH, MgH_2, $LiBH_4$, $NaBH_4$, BeH_2, TiH_2 and ZrH_2
- Pd (and alloys) with absorbed H
- Hydrocarbons (polyethylene or $(CH_2)_n$) with boron
- Quasi-crystals, eg. $(TiZrNi)_1\ H_{1.7}$
- Condensed hydrogen (solid and liquid)

Water, while not on the list given us, is carried in large masses on manned missions and is an important and efficient shielding material. We further note that the list of materials considered is not inclusive and that other hydrogen rich compounds may exist for application as viable shielding.

Table 1 shows these materials with their relevant properties. The key data in this table are (1) the weight % of hydrogen, and (2) the atom density of H (the number of H atoms per cm^3). It is well established that H provides the best shielding protection against GCRs and therefore, the aim is to maximize its incorporation. To this end, using the dose curves of Wilson, *et al.,* 1995, 1997 and Simonsen, *et al.,* 1997*,* and the materials data in Table 1, we have considered the following characteristics:

- The efficiency for dose reduction (must be calculated for each case)
- The weight efficiency
- The volume efficiency
- Other considerations: dual use, toxicity, ease of handling, safety, structural applications, material properties such as thermal and electrical conductivity.

Table 1
Volume and Mass Density of Hydrogen Contained in Materials

	H_2(s) or (1)	LiH	BeH_2	MgH_2	$LiBH_4$	$NaBH_4$	CH_2/n	H_2O	Pd/Ag	Nano-Carbons	Quasi Crystals	Al
density (g cm^{-3})	~.07	0.78	0.65	1.45	0.66	1.07	0.92	1.0	~10.0	?	?	2.7
wt % H	100	12.7	18.3	7.7	18.4	10.7	14.3	11.2	1-4	6 (to 20%+)	2.5	-
atom % H	100	50	67	67	67	67	67	67	>100	30 to >100	67	-
H atoms cm^{-3} ($x10^{22}$)	5.3	5.9	7.8	6.5	7.2		7.9	6.7	20?	?		-

It is noted that, while the weight efficiency (compared to pure H_2) of all the materials considered varied from 5-20% H, the volume efficiency of all the materials is similar. Where the data are reasonably well known, all showed a H density on the order of $6\text{-}7x10^{22}$ atoms cm^{-3}. In fact, the lowest density of the group is condensed H_2 at $5\text{-}6x10^{22}$. This volume efficiency number gives an idea of how thick the shielding layer would have to be, assuming the bulk of the shielding is provided by the hydrogen. The volume efficiencies are not considered well known for carbon nano-materials or palladium alloys.

Novel Materials

<u>Carbon Nano-materials</u>

This group includes carbon nano-tubes, fullerenes (buckyballs) and nano-fibers. There is currently considerable interest in them from a nano technology standpoint and development that includes diverse applications. Funding is supplied (in the US) by NSF, DOE, and NASA and the literature is vast and quickly growing. In the present context we have reviewed some studies of the materials for hydrogen storage (the DOE hydrogen storage program). A reference review is given by Dresselhaus, November 1999. We found no reference to studies of the material for application as a radiation shield. The panel briefly interviewed M. J. Heben of the DOE National Renewable Energy Laboratory, an active researcher in the hydrogen storage area.

Weight % of storage of H in nano-carbons seems well-documented at the 6% level, but claims of up to and exceeding 20% have been published (see Dresselhaus). For comparison, our reference material is polyethylene $(CH_2)_n$, hydrocarbon polymer, with a H content of 14% by weight (see Table 1).

Further Studies: In light of the facts that:

- C is probably the next most efficient GCR shielding element to H
- Nano-carbons store large amounts of H
- Nano-carbons can have very large material strengths, as well as useful electrical and thermal conductivities. Thus, the number of dual-use opportunities appear greater than with polymers such as polyethylene

We recommend that NASA study the H storage capabilities of nano-carbons, and their chemical and physical properties. It is important that NASA keeps abreast of this rapidly moving research field.

Metal Hydrides: LiH, BeH_2, MgH_2, $LiBH_4$, $NaBH_4$, TiH_2, ZrH_2

Metal hydrides are an efficient means of storing hydrogen, with composition by weight from 7 to 18% hydrogen. LiH is castable and has long been considered for space application (Welch, 1974) and remains the benchmark in this group. Other hydrides contain heavier metals (with reduced dose-reduction efficiency) and lower mass efficiency (ZrH_2, TiH_2, $NaBH_4$). BeH_2, with uncertain reactivity and toxicity offers little advantage over LiH except in mass efficiency. $LiBH_4$, the most mass efficient in the group at 18.4% H is considered worthy of study. Only a radiation transport calculation or accurate experimental evaluation will show if the presence of B in the material will counteract its higher H content (with respect to LiH) as a GCR shield.

Metal hydrides react with air and moisture, though with different rates. They are being considered as an H storage medium by the Department of Energy hydrogen storage program. Typically the H_2 is released for use as a fuel by the addition of water to the hydride. This reactivity is of concern if the material is inside the living compartment where oxygen and water are both present. LiH can be melted and cast in inert atmospheres into convenient forms.

Hydride reaction with water (which releases H_2) may serve a dual use by providing a source of fuel.

Further Studies: Stay abreast of current developments, especially in liaison with DOE. Evaluate the shielding effectiveness of these hydrides relative to polyethylene using a transport code such as HZETRN. Study mechanical properties, reactivity and packaging, and hazards abatement.

Palladium Alloys

Palladium has long been known for its ability to dissolve hydrogen. The theoretical solubility of H in pure Pd approaches a 1:1 atomic ratio, or about 1% by weight of H. Pd alloyed with silver may extend this limit to 4% or more. If true, the Pd/Ag/H system would provide the largest atomic ratio of H in any combinational materials system.

We are not aware of any published studies considering Pd/H as a shielding material.

Other Comments: While Pd is very expensive (and relatively heavy), it is unique in its behavior with hydrogen. Other useful properties include electrical and thermal conductivity, mechanical strength, and corrosion resistance.

Further Studies: We recommend investigating the Pd alloy system’s ability to store hydrogen as well as assessing its potential to serve as a shielding material. We also recommend the shielding effectiveness be compared with polyethylene using a transport code such as HZETRN.

Borated Polyethylene $(CH_2)_n$

Polyethylene is a cheap, readily available hydrocarbon polymer with established shielding capabilities in the GCR energy field. High density polyethylene is already an approved material for use in manned space missions. It is one of the reference shielding materials used by the panel, and its shielding properties have been calculated (e.g. by Wilson, *et al.,* 1992 [Figs. 1, 2]).

Polyethylene may readily be cast or hot-pressed into slabs or arbitrary shapes, however, it has poor mechanical characteristics (low strength, poor dimensional stability). The potential for dual-use seems, therefore, rather low.

The addition of B compounds to the matrix has been suggested for the purpose of absorbing thermal neutrons, a major concern for human exposure. However, radiation transport calculations (e.g., Wilson, *et al.,* 1997) clearly show that the addition of boron slightly increases the tissue dose below the absorber, presumably due to the increased likelihood of fragment emission from the boron nuclei.

Further Studies: While particular shield configurations may need to be examined for potential boron incorporation, the panel believes this should be done by calculation and materials research studies are not recommended. We do recommend engineering studies aimed at incorporating polyethylene as spacecraft components.

Quasi-crystals (Alloys of TiZrNi)

These unusual materials have been studied in programs funded by the DOE, NSF, and NASA (e.g., see Kelton, K.F., Washington University). The uneven packing of metal atoms in the lattices appears to permit absorption of relatively large amounts of hydrogen (1-2.5% by weight). No evidence of research on shielding applications was found by the group, likely in view of the relatively low H storage efficiency and the high Z of the component metals.

Further Studies: Not recommended

Solid Hydrogen

Pure hydrogen has the best shielding performance for the GCR environment of all materials per unit mass. To be used efficiently it must be condensed into a solid or liquid.

A scenario has been proposed (Post) in which the uniquely beneficial shielding properties of solid H_2 against the GCR field would be used. Utilizing relatively cheap unmanned rockets large H_2 snowballs could be lifted to orbit, released, and then ‘strapped’ onto a Mars-bound vehicle. The snowballs would be encased in efficient insulation and vented to space. Arguments have been made that handling solid H_2 under these conditions would be much easier than liquid H_2. These arguments did not persuade the panel.

Further Studies: Not recommended

Liquid Hydrogen

Large volumes of liquid H_2 are routinely carried into space as fuel and the holding/transport technology seems well-developed. Several of the Martian Mission plans, whether chemical- or nuclear-rocket-powered, involve the transport of large masses (tens of tons) of liquid H_2. Although not a “novel material,” it seems prudent to consider using part of this fuel as radiation shielding for the crew, rather than transporting many tons of passive shielding which would have no dual or contingency use. This would presumably require considerable departures from current vehicle design configurations.

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Appendix B

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ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield **Concept: Magnetic Fields with Local Strong Magnets**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes No X

Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes No X

Explain: The mass of the coil will be very large. The stored energy will be very large. A very strong structure would be required to support magnet coils.

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? If superconductors are used for the magnet, a quench would release a dangerous amount of energy.

6. How does it compare with other ideas in the category? Poorly

Advantages: None

Disadvantages: Launch mass would exceed that of passive shielding due to structure required to support magnet coils.

Other Comments:

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation:

Submitted by: Jim Adams

ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield **Concept: Plasma Inflated Field**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Propulsion

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: A model for vacuum chamber tests is under construction at MSFC now.

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards?

6. How does it compare with other ideas in the category? It is the best of this category.

Advantages: Probably can be scaled to provide adequate protection while keeping the mass and stored energy reasonable. Power to replace plasma is also possibly reasonable.

Disadvantages: Produces its own radiation belts? Stability of plasma. Loss of plasma at field boundaries with solar wind.

Other Comments:

Recommend future research for the radiation shielding program? Yes X No

If yes briefly describe next phase of investigation: The outstanding questions about the concept need to be answered. If a careful study of the model demonstrates that it still shows promise of providing adequate shielding then work should begin on a test model. The first step is a detailed review of calculations/estimates for a system that would provide $\left|\int_L \vec{B} X d\vec{l}\right| = 1000$ for GCR shielding, and a review of vacuum chamber test results. Next, cosmic rays should be traced through the field to determine its shielding effectiveness.

Submitted by: Jim Adams

ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield **Concept: Pure Electrostatic Shield**

1. Does it obey the laws of physics? Yes X No

2. Could it
a. Reduce the GCR flux significantly? Yes X No
b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes No X
Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes No X
Explain: While the concept does not violate the laws of physics, recharging the field because of leakage to the space plasma, will require a large power source. Charging the spacecraft will require a particle accelerator capable of 10 GeV energy.

5. Are there significant safety issues that the engineering must address? Yes X No
What are the hazards? Large positive charge on spacecraft to produce ~10 GV potential. Electrons from space plasma will have 10 GeV energy when they impact on spacecraft. They will cause electromagnetic showers extending into the crew quarters.

6. How does it compare with other ideas in the category? It has a low score relative to the plasma concepts.
Advantages: None
Disadvantages: Many significant complications in design/implementation
Other Comments: With electrostatic potentials so large, prevention of arc discharges seems impossible. The vehicle will have to be very large.
Recommend future research for the radiation shielding program? Yes No X
If yes, briefly describe next phase of investigation:

Submitted by: John Watts

ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield

Concept: Electrostatic from 'Exotic Ideas' (Natural Spacecraft Charging)

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes No X

b. Reduce the GCR dose significantly? Yes No X

3. Does it have dual use? Yes No X

Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes No X

Explain: Will not work at galactic cosmic ray energies. GCRs are thousands of MeV and require electrostatic potentials of 10,000 of MV (million volts) for shielding them. Spacecraft charging, even with grids, could not come close.

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards?

6. How does it compare with other ideas in the category? Lowest score

Advantages. None

Disadvantages:

Other Comments: This idea could generate low electrostatic potentials, but the principal radiation problem is with GCR, requiring ~ 10^{10} volts.

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation:

Submitted by: John Watts

ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield **Concept: Plasma Electrostatic Shield**

1. Does it obey the laws of physics? Yes X No

2. Could it
a. Reduce the GCR flux significantly? Yes X No
b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes No X
Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes No X
Explain: There would be large charge losses due to electron scattering losses, out-gassing from the spacecraft and other sources. These losses would need to be replaced by a high voltage particle accelerator. To shield against GCR, one still needs ~ 10^{10} volts. Access to the spacecraft would be prohibited without discharge of the voltage. The spacecraft vehicle would have to be at least 10 km in diameter.

5. Are there significant safety issues that the engineering must address? Yes X No
What are the hazards? Large positive charge (~1 coulomb) on spacecraft to produce ~10 GV potential. Failure of magnet, or possibly instabilities in the electron cloud, would discharge the trapped charge onto the spacecraft (very large discharge).

6. How does it compare with other ideas in the category? It has a low score relative to the neutral plasma concepts but higher than pure electrostatic.
Advantages: The spacecraft/electron cloud combination would appear neutral relative to the space plasma and thus would not be immediately discharged as a pure electrostatic shield would.
Disadvantages: Plenty. Implementation would require exceptional high voltage engineering.
Other Comments: The published concept and study (Levy, 1962) was for a short term ~ 1 day shield against solar particle events. Shielding against galactic cosmic rays would be required over the entire mission and an up-scaling of potential by more than two orders of magnitude.
Recommend future research for the radiation shielding program? Yes No X
If yes, briefly describe next phase of investigation:

Submitted by: John Watts

ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield **Concept: Large Coil**

1. Does it obey the laws of physics? Yes X No

2. Could it
a. Reduce the GCR flux significantly? Yes X No
b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No
Describe other use: Propulsion

4. Is a practical implementation and engineering solution conceivable? Yes X No
Explain: There are many questions about the practicality that needs to be addressed, including the actual shielding achievable and the numbers and sizes of coils needed for GCR shielding, as well as deployment problems, passive cooling, etc.

5. Are there significant safety issues that the engineering must address? Yes X No
What are the hazards? Dangerously high stored energy

6. How does it compare with other ideas in the category? Ranks second.
Advantages: Potential of providing adequate shielding, without massive structure to support coils, large stored energy, and risks from large magnetic field.
Disadvantages: Huge stored energy. How to deploy? Stability of the coil? Stress in the coil? Mass of the structure? How to keep cool? Does it develop radiation belts?
Other Comments: While a single large coil will not work, it may be possible to find a multicoil configuration that will produce a magnetic field of ~ 100 gauss over most of a spherical volume of radius 10 km. This would be an effective shield for GCRs.
Recommend future research for the radiation shielding program? Yes X No
If yes, briefly describe next phase of investigation: A search should be made for a multi-coil configuration that will work.

Submitted by: Jim Adams

ASSESSMENT OF ADVANCED CONCEPT

Category: Active (Electromagnetic) Shield **Concept: Large Sail/Shield**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes No X

b. Reduce the GCR dose significantly? Yes No X

3. Does it have dual use? Yes No X

Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes No X

Explain: It would require a huge shield to be held at a great distance from the vehicle by means of some structural elements. The scale of the shield makes its engineering hard to conceive.

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards?

6. How does it compare with other ideas in the category? Poorly

Advantages: None

Disadvantages: Requires a huge shield to be deployed, but the shield would be partially effective only against solar energetic particles, probably only in the early part of each event.

Other Comments:

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation:

Submitted by: Jim Adams

ASSESSMENT OF ADVANCED CONCEPT

Category: Extra-terrestrial Materials **Concept: Comet**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Availability of water. Detailed study of comets.

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: Approach, landing, and burrowing in a comet is technically feasible, but presents enormous engineering challenges, particularly for manned flight. Among the most serious challenges are the complex and unpredictable dust environment near an active comet nucleus, the unknown density, porosity, and material strength of cometary surfaces, and the lack of comets on orbits with practical combinations of perihelion, aphelion, and inclination.

5. *Are there significant safety issues that the engineering must address?* Yes X No

What are the hazards? i. Dust leaving a comet is accelerated near the surface to a velocity of order 1 km/s (reference: see report). Spacecraft would need to be shielded against impact with both microscopic dust and macroscopic fragments flowing out from the surface.

ii. Cometary activity is seen in objects even at large heliocentric distances (e.g. 2060 Chiron at ~10 AU). This activity is episodic and unpredictable. Landing near a latent site of activity or burrowing into a high-pressure pocket of trapped volatiles could prove catastrophic to a mission.

6. *How does it compare with other ideas in the category?* Comets have the same advantages as asteroids, but many more disadvantages.

Advantages: It is possible to get a large amount of mass shielding without the energy cost of launching the mass or propelling it into a planet-crossing orbit. Cometary water is a potentially valuable resource.

Disadvantages: Unknown, unpredictable environmental hazards would jeopardize the safety of astronauts. Comets with suitable orbits are very rare to non-existent. Our search of a comet data base yielded no reasonable candidate in the next 20 years.

Other Comments:

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation:

Submitted by: Keith Noll

ASSESSMENT OF ADVANCED CONCEPT

Category: Extra-terrestrial Materials **Concept: Asteroids**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Scientifically interesting material.

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: One might find an asteroid that swings by Earth and then Mars that requires little penalty in orbital energy to rendezvous with asteroid and depart for Mars. However, an alternate object would be required for the return or the mass used for shielding would need to be carried with you to Mars and back to Earth.

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? Concerns about low gravity of asteroid and integrity of asteroidal material in capture (grappling) and mining or covering spacecraft with a thick layer of material.

6. How does it compare with other ideas in the category? Better than comets

Advantages: Mass may be already directed towards Mars or Earth.

Disadvantages: Probability of finding such objects is very small. Any such objects are likely to be short lived due to encounters with Earth and Mars. 1000 objects known (estimated to be 10% of total) of these ? (0) are energetically reasonable with the present database

Other Comments: Extremely unlikely to find a ‘family’ of objects to use as shields. This leaves the possibility of using a single asteroid as source of shield material that is retained at Mars for return trip.

Recommend future research for the radiation shielding program? Yes X No

If yes, briefly describe next phase of investigation: Continue to examine database

Submitted by: Workshop participant; (David Hathaway review)

ASSESSMENT OF ADVANCED CONCEPT

Category: Extra-terrestrial Materials **Concept: Asteroids**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes No X

Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes No X

Explain: The delta velocities (ΔVs) are too large to make this feasible. The capture ΔV at the asteroid ranges from 3-17 km/s (compared to 0-1.8 km/s for capture at Mars), due to timing and relative geometry. Departure ΔVs from the asteroid will have the similar 3-17 km/s magnitudes, since relative geometries between the asteroid and Mars are rarely ideal. The asteroid must pass sufficiently close to both Earth and Mars on the same outbound orbit, while a different asteroid would have to be utilized similarly for the return to Earth.

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? Large ΔVs require large propellant loads, which require long burn times on the engines, creating a reliability/safety concern with the propulsion subsystem. Additional burns would also be needed to stop at and depart from the asteroid, which are not required in the nominal mission.

6. How does it compare with other ideas in the category?

Advantages: i. Over the Comet option: There are more asteroids than comets to use, especially those near the appropriate energy levels that are usable for ‘hitch-hiking’ to Mars.

ii. Over the Earth Orbital Debris option: The amount of energy expended to collect sufficient mass to build the required shielding from orbital debris would likely be greater than that necessary for the asteroid mission.

iii. Over the Lunar Resources Option: Using Lunar regolith requires ΔVs to stop at the Moon, descend to the surface, ascend back up to orbit, and then inject onto a Mars trajectory, most ΔVs while carrying the additional shield mass.

Disadvantages: i. The likelihood that there are a pair of asteroids that satisfy the mission trajectory requirements are extremely small, due to the required similarity ($<2+°$ difference in orbital plane, $<2+°$ difference in flight path angle, <few days difference in timing/phasing) of the asteroid orbit to that of both Earth and Mars.

ii. The energy requirements to accomplish advantageous use of an asteroid from a radiation perspective penalize the stack mass to an extent that the mission could be more easily done lifting additional shielding from Earth’s surface that would already be optimized/customized for use on the Mars piloted hab/stack.

Other Comments: There does not appear to be any reasonable option in the Extra-terrestrial Concepts section to reduce the radiation that the crew would experience on a Mars exploration mission. Other solutions must be found to meet the new radiation exposure limits.

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation:

Submitted by: Larry Kos

ASSESSMENT OF ADVANCED CONCEPT

Category: Extra-terrestrial Materials **Concept: Artificial Space Debris (Large Objects)**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Possibility of improving the space environment by removing debris.

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: Yes, but not easy. Requires matching velocity/orbit with several (or more) objects, capturing and possibly reforming. Requires time and energy — could be LEO or GEO.

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? Residual fuel and other toxics (probably not insurmountable).

6. How does it compare with other ideas in the category?

Advantages: Reliable. Availability of fairly large amount of mass in known orbits, can catch with precursor 'garbage collector' satellite.

Disadvantages: Can't get a one-step solution, as with an asteroid. Complex debris accumulation strategy.

Other Comments: 'Space garbage collection' might be environmentally popular. Relaxing of radiation standards would make it more practical. Present required shield mass estimate is about 150 tonnes of aluminum (part of which is already in the transit vehicle structure/ equipment TAP)

Recommend future research for the radiation shielding program? Yes X No

If yes, briefly describe next phase of investigation: There should be a more specific study using the space catalog of which actual objects/categories are best to use together with energy expenditures, capture mass, and materials. Also a 'white paper' on a proposed capture mechanism, including tethering or cruising after capture.

Submitted by: Steve Knowles

ASSESSMENT OF ADVANCED CONCEPT

Category: Extra-terrestrial Materials **Concept: Artificial Space Debris (Large Objects)**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No
b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Surrounding critical parts of spacecraft with debris material will also provide protection from impacting meteoroids.

4. Is a practical implementation and engineering solution conceivable? Yes No X (with current state-of-the-art)

Explain: Costly from an energy standpoint to gather up the debris. After collection the debris must be processed to produce usable shielding blocks/plates which will also be costly from energy standpoint – primarily aluminum, poor shielding.

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? Debris may contain flammable or explosive materials (propellant, pyrotechnic devices, etc.), structural integrity of blocks of debris shielding poor.

6. How does it compare with other ideas in the category? All ideas proposed to use E.T. materials have severe problems associated with them.

Advantages: Orbiting debris has energy of orbit.
Disadvantages:
Other Comments:
Recommend future research for the radiation shielding program? Yes No X
If yes, briefly describe next phase of investigation:

Submitted by: Workshop participant; (David Hathaway review)

ASSESSMENT OF ADVANCED CONCEPT

Category: Novel Materials **Concept: Borated Polyethylene**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes No X

Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: It could be used in the same way as polyethylene.

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards? Somewhat flammable

6. How does it compare with other ideas in the category? Polyethylene is currently the best 'standard or non-novel' solid shielding material in terms of shield weight. (However shielding calculations indicate the addition of ~20% boron slightly degrades shielding. TAP)

Advantages: High hydrogen content, cheap

Disadvantages: Non-structural

Other Comments: Insulation?

Recommend future research for the radiation shielding program? Yes X No

If Yes, briefly describe next phase of investigation: Perform calculations with improved codes to evaluate relative shielding effectiveness, how much B?, how bonded?

Submitted by: John Gregory

ASSESSMENT OF ADVANCED CONCEPT

Category: Novel Materials **Concept: Quasi-crystals**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes No X

b. Reduce the GCR dose significantly? Yes No X

3. Does it have dual use? Yes No X

Describe other use:

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: Need to fabricate, fill with hydrogen, bind into other engineering material.

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards?

6. How does it compare with other ideas in the category?

Advantages: Better than Al in shielding?

Disadvantages: Contains high Z material (TiZrNi), producing a lot of neutrons in interactions, hydrogen only 2.5% by weight wt (max), hard to fabricate into shields

Other Comments: Of interest for hydrogen storage. Worthwhile to periodically survey literature for improvements in this field.

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation: Need to evaluate with shielding calculations the relative shielding effectiveness of all materials on list.

Submitted by: John Gregory

ASSESSMENT OF ADVANCED CONCEPT

Category: Novel Materials **Concept: Hydrogen (condensed)**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Fuel cell, propulsion.

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: Solid H_2 has been proposed for 10 year life in space, if properly insulated

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? Pressure and temperature instability, must be outside cabin.

6. How does it compare with other ideas in the category?

Advantages: Best shielding per unit mass, Good dual uses

Disadvantages: Low latent heat (liquid?)

Other Comments:

Recommend future research for the radiation shielding program? Yes No X

If yes, briefly describe next phase of investigation: Best shielding per unit mass, no particular advantages seen for solid vs. liquid; solid is slightly less dense, is not rigid, expensive to make. Large volumes of liquid hydrogen are utilized on mission

Submitted by: John Gregory

ASSESSMENT OF ADVANCED CONCEPT

Category: Novel Materials **Concept: Metal Hydrides**

1. Does it obey the laws of Physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Use in fuel cells.

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: LiH is stable, castable in slabs or complex forms, can be pressed.

5. Are there significant safety issues that the engineering must address? Yes X No

What are the hazards? Flammable, react with water, water vapor

6. How does it compare with other ideas in the category?

Advantages: Good shield per unit mass, good neutron absorber; LiH almost competitive with polyethylene as shield.

Disadvantages: Reactive, poor mechanical properties

Other Comments: Several hydrides are candidates for study: LiH, MgH_2, $LiBH_4$, TeH_2

Recommend future research for the radiation shielding program? Yes X No

If yes, briefly describe next phase of investigation: Evaluation of all candidates with transport codes for relative shielding effectiveness, encapsulation and hazard abatement.

Submitted by: John Gregory

ASSESSMENT OF ADVANCED CONCEPT

Category: Novel Materials **Concept: Nano-carbons**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Potential use in composite structures; hydrogen storage; useful in fuel cells

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: Composite materials for structural applications

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards? Flammable

6. How does it compare with other ideas in the category?

Advantages: Low Z, good H_2 retention at room temperature, thermally and electrically conductive

Disadvantages: 6% by wt H storage confirmed. Reports of higher values.

Other Comments: Expensive at present.

Recommend future research for the radiation shielding program? Yes X No

If Yes, briefly describe next phase of investigation: Claims in literature for special forms of nano-carbon indicate much higher H_2 retention is possible. Evaluate relative shielding effectiveness with various assumed H content.

Submitted by: John Gregory

ASSESSMENT OF ADVANCED CONCEPT

Category: Novel Materials **Concept: Palladium/Silver**

1. Does it obey the laws of physics? Yes X No

2. Could it

a. Reduce the GCR flux significantly? Yes X No

b. Reduce the GCR dose significantly? Yes X No

3. Does it have dual use? Yes X No

Describe other use: Mechanically strong, electrically conductive, corrosion resistant

4. Is a practical implementation and engineering solution conceivable? Yes X No

Explain: Easy to fabricate, easy to charge with H

5. Are there significant safety issues that the engineering must address? Yes No X

What are the hazards?

6. How does it compare with other ideas in the category?

Advantages: High hydrogen content.

Disadvantages: High atomic mass elements, probable high neutron production, expensive

Other Comments: Conductive, corrosion resistant, unreactive

Recommend future research for the radiation shielding program? Yes X No

If yes, briefly describe next phase of investigation: Uncertainty about maximum hydrogen absorption. Potential for higher hydrogen atom ratio than any other known material, which should be investigated.

Submitted by: John Gregory

Appendix C

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Preliminary Report of the
Advanced Radiation Protection Working Group

Julie Swain M.D., HQ
Guy Fogleman Ph.D., HQ
Eugene Trinh, Jr. Ph.D., HQ
Frank Cucinotta Ph.D., JSC
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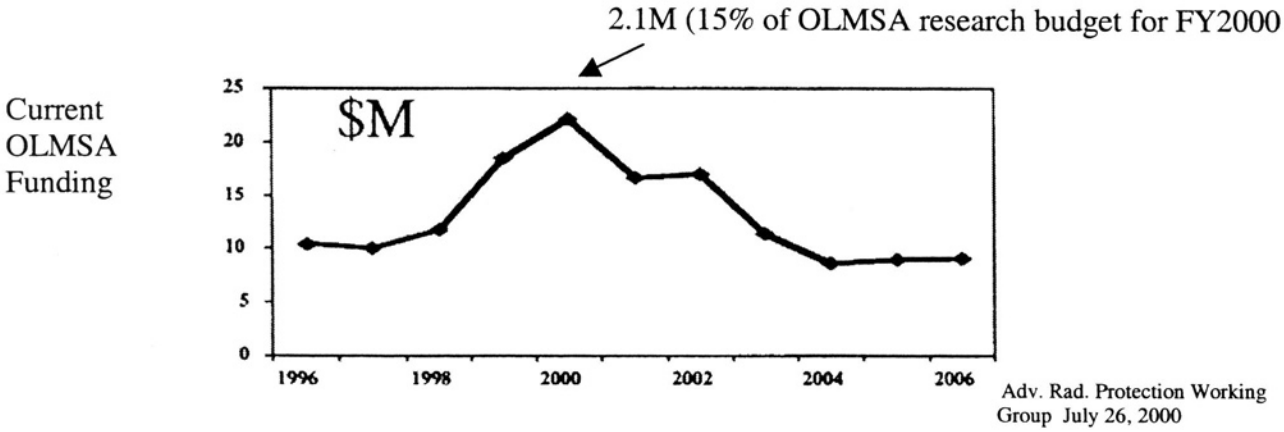
Assumptions: The current evolutionary projects in radiation protection will be continued in:

a. Defining the radiation environment (destination-specific)
b. Biological dose tolerance limits of each type of radiation for each side effect in each type of tissue; dev. of animal models
c. Operational studies to minimize radiation exposure
d. Define shielding required with known materials

(This radiation research plan has been validated by the NRC and outside experts.)



Revolutionary Physical Sciences Radiation Protection Strategies

1. Magnetic Fields

- Any dipole field in space will develop a radiation belt like that of Earth by capturing charged particles that move along field lines
  - The rings of Saturn act as a radiation shield, reducing captured charged particles
- Solution: Develop a tethered magnet/spacecraft system with a thin, shielding disk (or disk sector) in the equatorial plane of the magnetic field to de-energize the moving particles
  - Possibly dual-use in that the solar wind pushing against the field will lead to propulsion
  - Plasma injection can expand the volume of the field
  - Problem: Huge energy storage and potential uncontrolled release

2. Electrostatic Fields

- In space, a small electrostatic potential imposed on a grid will naturally build a high voltage field that will act to deflect low energy charged particles
- Problem: The photoelectric effect produces a cloud of cold electrons around a spacecraft
  - This would neutralize the net positive charge of the grid
  - A second, outer, negative potential grid could possibly mitigate this problem

3. **<u>Use extraterrestrial materials for shielding</u>**

- Collect and assemble "space junk" from geosynchronous orbit to serve as a shield
- For Mars transit, mine water ice or regolith on the moon and use it to shield the spacecraft enroute
- For Mars exploration, mine/drill to the "aquifer" for ice (water) for habitat protection, ISRU, and life support
- Precursor radiation measurements on Mars surface can be used to locate areas with natural atmospheric and terrain shielding leading to 25% exposure reduction
- Place the spacecraft within a huge cloud of neutral gas or debris (i.e. floating dust) that is electrostatically or magnetically controlled
- Far Out Concept™: Capture a ride on and burrow into a short-period comet (from the Kuiper belt, 3.3-10 year period)

Revolutionary Radiation Shielding Materials

4. **<u>Projected Advanced Materials</u>** (Very low TRL, at Fundamental Research Stage)

- Hydrogen loaded Single Walled Nanotubes and Fullerenes
  – Dual use — radiation protection and structural modifier in aluminum alloy composites
  – Department of Energy is interested for hydrogen storage
- Borated Polyethylene
  – Boron acts as a neutron absorber, improving the shielding performance of conventional polyethylene
- Hydrogen loaded Palladium-Silver (Pd-Ag) alloys
  – Dual use — radiation shielding and hydrogen storage
- Hydrogen loaded Metal hydrides
  – Dual use — radiation shielding and hydrogen storage

5. **<u>Design spacecraft according to human requirements!!</u>**

- Previous spacecraft design has been based on engineering requirements and humans have adapted to fit the vehicle
- Design requirements and materials could be tailored to human compatibility and protection

6. <u>Biomedical Research</u>

- Astronaut Genetic Screening
  Some humans are relatively radioresistant, others are more sensitive to radiation damage
  – Solution: Determine the genetic markers for radioresistance, then screen in those with this genetic profile while screening out those with sensitivity
  – Problem: Ethically unacceptable at this time
- Gene Therapy
  – The genetic sequences responsible for the incredible radioresistance of certain microorganisms are being determined
  – Solution: Administer genetic therapy to astronauts in order to synthesize and secrete the proteins responsible for radioresistance
  – Problem: Gene therapy is, as yet, unsuccessful. This is ethically unacceptable at this time
- Pharmacologic Therapy
  – Solution: Use tissue-specific inhibitors of radiation damage to prevent radiation damage or use pharmacologic agents to induce rapid, accurate DNA repair. Administer selective apoptosis inhibitors and promotors, depending on reversibility of radiation damage.
  – Problem: No such drugs are known at this time

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Appendix D

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Appendix E

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References and Literature Survey

Cosmic Ray Shielding Papers

Adams Jr., J., Silberberg, H.R., and Tsao, C.H. Cosmic Ray Effects on Microelectronics, Part I: The Near-Earth Particle Environment. NRL Memorandum Report 4506, 25 August 1981(1981)

Adams, Jr., J.H., Letaw, J.R., and Smart, D.F. Part II: The Geomagnetic Cutoff Effects. NRL Memorandum Report 5099, 26 May 1983 (1983)

Adams, Jr., J.H. Cosmic Ray Effects on Microelectronics (CREME), Part IV. Naval Research Laboratory Memorandum Report 5901, (31 December 1986)

Adams, Jr., J.H. Cosmic Radiation: Constraints of Space Exploration. *Radiation Measurement,* 20(3), 397-401 (1992)

Armstrong, T.W. Private Communications, plotted from HZETRN calculations by Wilson, J.W., in NASA TM 3662 (1997)

Armstrong, T.W. and Colborn, B.L. Cosmic Ray and Secondary Particle Environment Analysis for Large Lunar Telescope Instruments. Science Applications International Corporation Report SAIC-TN-912 (May 1991)

Armstrong, T. and Chandler, K.C. HETC: A High Energy Transport Code. *Nucl. Sci. Engr.,* 49, 110 (1972)

Badhwar, G.D. and O'Neil, P.M. Galactic Cosmic Radiation Model and Its Application. *Advances in Space Research,* 17, 7-17 (1996)

Bendel, W.L. and Petersen, E.L. Proton Upsets in Orbit. *IEEE Trans. Nucl. Sci.* 30,4481. (1983)

Chenette, D.L., Chen, J., Clayton, E., Guzik, T.G., Wefel, J.P., Garcia-Munoz, M., Lopate, C., Pyle, K.R., Ray, K.P., Mullen, E.G., and Hardy, D.A. The CRRES/SPACERAD Heavy Ion Model of the Environment (CHIME) for Cosmic Ray and Solar Particles Effects on Electronic and Biological Systems in Space. *IEEE Trans. on Nucl. Sci.,* 41(6) (December 1994)

Colborn, B.L., Ringler, S.J., Potter, D.W., and Armstrong, T.W. CADrays 3-D Mass Model of International Space Station Alpha. Science Applications International Corporation Report SAICTN-9502 (February 1995)

Croley, D.R., Garrett, H.B., Murphy, G.B., and Garrard, T.L. Solar Particle Induced Upsets in the TDRS-1 Attitude Control System RAM During the October 1989 Solar Particle Events. *IEEE Trans. Nucl. Sci.* NS-42. p. 1489 (1995)

Cucinotta, F.A., private communication (2000)

Feynman, J., Spitale, G., and Wang, J. Interplanetary Proton Fluence Model: JPL 1991. *Journal of Geophysical Research,* 98, 13281 (1993)

Jordan, T.M. NOVICE, a commercial code available from E.M.P. Consultants.

Kahler, S.W. Solar Flares and Coronal Mass Ejections. Ann. Rev. *Astron. Astrophys.* 30, 113 (1992)

Letaw, J.R. Space Radiation, a commercial code available from Space Radiation Associates.

Letaw, J.R., Silberberg, R., and Tsao, C.H. Galactic Cosmic Radiation Doses to Astronauts Outside the Magnetosphere. *Terrestrial Space Radiation and Its Biological Effects.* P.D. McCormack, C.E. Swenberg, and H. Bucker, eds. Plenum Publishing Co., p. 663 (1988)

Majewski, P.P., Normand, E. and Oberg, D.L. A New Solar Flare Heavy Ion Model and its Implementation Through MACREE, An Improved Modeling Tool to Calculate Single Event Effect Rates in Space. *IEEE Trans. Nucl. Sci.* NS42. p. 2043 (1995)

National Council on Radiation Protection (NCRP) Report No. 98. National Council on Radiation Protection and Measurement, 7910 Woodmont Ave., Bethesda, MD 20814 (1989)

Nelson, J.C. Life Sciences Program Tasks and Bibliography for FY 1996. NASA TM-4801 (May 1997)

Nymmik, R.A., Panasyuk, M.I., Pervaja, T.I., and Suslov, A.A. A Model of Galactic Cosmic Ray Fluxes. *Nucl. Tracks Radiat. Meas.* 20, 427 (1992)

Parnell, T.A. Report of the Materials Science Panel on Radiation Shielding Materials, Workshop on Research for Space Exploration. Cleveland, OH. Aug. 5-7, 1997 (proceedings in press) (1997)

Parnell, T. A., Watts, J.W., and Armstrong, T.W. “Radiation Effects and Protection for Moon and Mars Missions.” in “Space 98,” Proceedings of Space Robotics, ACCE, Reston, VA (1998)

Petersen, E.L. SEE Rate Calculations Using the Effective Flux Approach and a Generalized Figure of Merit Approximation. *IEEE Trans. Nucl. Sci. Vol.* 42 (1995)

Petersen, E.L., Pickel, J.C., Adams Jr., J.H., and Smith, E.C. Rate Predictions for Single Event Effects - A Critique. *IEEE Trans. Nucl. Sci.* NS-39, p.1577 (1992)

Pickel, J.C. Single-Event Effects Rate Predictions. *IEEE Trans. Nucl. Sci.,* 32, 483 (1996)

Pickel, J.C. and Blandford, Jr., J.T. Cosmic Ray Induced Errors in MOS Memory Cells. *IEEE Trans. Nucl. Sci.* NS-27 (1980)

Rossi, H.H. and Zaider, *M. Microdosimetry and Its Applications.* Springer Verlag (May 1995)

Sauer, H.H., Zwicki, R.D., and Ness, M.J. Summary Data for the Solar Energetic Particle Events of August through December 1989. Space Environment Laboratory, National Oceanic and Atmospheric Administration (1990)

Seltzer, S.M. Updated Calculations for Routine Space-Shielding Radiation Dose Estimates: SHIELDOSE-2. National Institute of Standards and Technology, NISTIR-5477 (December 1994)

Shea, M.A and Smart, D.F. A Summary of Major Solar Proton Events. *Solar Phys.,* 127, 297-320 (June 1990)

Shea, M.A. and Smart, D.F. History of Energetic Solar Protons for the Past Three Solar Cycles Including Cycle 22 Update. *Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Part B.* C.E. Swenberg *et al.,* eds. New York: Plenum Press (1993)

Wilson, J.W., *et al.,* eds. Shielding Strategies for Human Space Exploration: A Workshop. Johnson Space Center, Houston, TX, December 6-8,1995 (1997)

Smith, E.C. Effects of Realistic Satellite Shielding on SEE Rates. *IEEE Trans. Nucl. Sci.* NS-41, p. 2396 (1994)

Smith, E.C. and Simpson, T.R. Predictions of Cosmic Radiation Induced Single Event Upsets in Digital Logic Devices in Geostationary Orbit. TRW report prepared for INTELSAT, (November 2, 1987)

Space Studies Board, National Research Council Report. Radiation Hazards to Crews of Interplanetary Missions. Washington, D.C., National Academy Press (1996)

Spillantini, P., *et al.* Radiation Shielding of Spacecraft in Manned Interplanetary Flights. NIM, A443, 254 (2000)

Stapor, W.J., Meyers, J.P., Langworthy, J.B., and Petersen, E.L. Two Parameter Model Calculations for Predicting Proton Induced Upsets. *IEEE Trans. Nucl. Sci. 37,* 1966 (1990)

Summers, G.P., Burke, E.A., Dale, C.J., Wolicki, E.A., Marshall, P.W., and Gehlhausen, M.A. Correlation of Particle-Induced Displacement Damage in Silicon. *IEEE Trans. Nucl. Sci., 34,* 1134 (1987)

Tada, H.Y. and Carter, Jr., J.R. Solar Cell Radiation Handbook. JPL Publication 77-56, (November 1, 1977)

Tsao, C.H., Silberberg, H.R., Adams, Jr., J., and Letaw, J.R. Part III: Propagation of Cosmic Rays in the Atmosphere. NRL Memorandum Report 5402, (9 August 1984)

Tylka, A.J., Dietrich, W.F., Boberg, P.R., Smith, E.C., and Adams, Jr., J.H. Single Event Upsets Caused by Solar Energetic Heavy Ions. *IEEE Trans. Nucl. Sci.,* 43, 2758 (1996)

Tylka, A.J., Adams, Jr., J.H., and Boberg, P.R., Brownstein, B., Dietrich, W.F., Flueckiger, E.O., Petersen, E.L., Shea, M.A., Smart, D.F., and Smith, E.C. CREME96: A Revision of the Cosmic Ray Effects on Micro-electronics Code. *IEEE Trans. Nucl. Sci.,* 44, 2150-2160 (1997).

Wiebel, B. Chemical Composition in High Energy Cosmic Rays. Fachbereich Physik Bergische Universitat, WUB 94-08 (April 1994)

Wilson, J.W., *et al.* Issues in Space Radiation Protection: Galactic Cosmic Rays." *Health Physics. V.* 68(1), 50-58 (1995)

Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Kahn, F., Nealy, J.E., Cucinotta, F.A., Simonsen, L.C., Shinn, J.L., and Norbury, J. W. Transport Methods and Interactions for Space Radiations. NASA RP-1257, Washington, DC (1994)

Wilson, J.W., *et al*. Improved Spacecraft Materials for Radiation Shielding. NASA Microgravity Materials Science Conference, July 14-16, 1998, NASA CP-1999-209092 (1999)

Wilson, J.W., *et al.* Improved Spacecraft Materials For Radiation Protection: Shield Materials Optimization and Testing. NASA Microgravity Materials Science Conference, June 6-8, 2000, NASA Conference Proceedings (In Press 2000)

Active (Electromagnetic) - Review Papers

Sussingham, J.C. Watkins, S. A., and Cocks, F.H. Forty Years of Development of Active Systems for Radiation Protection of Spacecraft. *Journal of Astronautical Sciences,* 47, 165-175 (1999)

Townsend, L.W. Overview of Active Methods for Shielding Spacecraft from Energetic Space Radiation. *Physica Medica* Vol. XVII, Supplement I, 84-85 (2001).

Active (Electromagnetic) - Electric Field

Beever, E.R., and Rusling, D.H. "The Importance of Space Radiation Shielding Weight." Proceedings of the 2nd Symposium on Protection Against Radiations in Space, A. Reetz, Jr., ed., NASA SP-169, 407-414 (1964)

Dow, N.F., Shen, S.P., and Heyda, J.F. Evaluations of Space Vehicle Shielding. General Electric Space Sciences Laboratory Report R62SD31 (April 1962)

Felten, J.E. Feasibility of Electrostatic Systems for Space Vehicle Radiation Shielding. *Journal of the Astronautical Sciences,* 11, 16-22 (1964)

Frisina, W. Optimizing Electrostatic Radiation Shielding for Manned Space Vehicles. *Acta Astronautica,* 12, 995-1003 (December 1985)

Kash, S.W. Minimum Structural Mass for a Magnetic Radiation Shield. *AIAA Journal,* 1, 1439 1441 (June 1963)

Kovalev, E.E., Molchanov, E.D., Nazirov, R.U., Riabova, T.Y., and Shneider, Y.G. "Electrostatic Shielding Against Cosmic Radiation and its Earth Applications." 24th International Astronautical Congress, Baku, Azerbaidzhan SSR, October 7-13, 1973, Paper (1973)

Kovalev, E.E., Molchanov, E.D., Pekhterev, Yu. G., Ryabova, T. Ya., Tikhomirov, B.I., and Khovanskaya, A.I. "An Investigation of the Basic Characteristics of Electrostatic Shielding from Cosmic Radiations on the Artificial Earth Satellite *Kosmos 605.* I. Measurement Procedure and the Complex of Scientific Apparatus." *Cosmic Research* 13(5), 687-692 (translated into English from *Kosmicheskie Issledovaniya* 13(5), 771-777.)

Kovalev, E.E., Molchanov, E.D., Pekhterev, Yu. G., Ryabova, T. Ya., and Tikhomirov, B.I. "An Investigation of the Basic Characteristics of Electrostatic Shielding from Cosmic Radiations on the Artificial Earth Satellite *Cosmos 605.* II. Results of Measurements" *Cosmic Research,* 14, 113-118 (1976) (translated from *Kosmicheskie Issledovaniya* 14(1) 126-132.) (1976)

Kovalev, E.E. and Riabova, T.Ia. "Study of Basic Electrostatic Radiation Shield Characteristics on Board the *Cosmos 605* Satellite." in "Life Science and Space Research XIV." Proceedings of the Open Meeting of the Working Group on Space Biology, May 29-June 7, 1975, and Symposium on Gravitational Physiology, Varna, Bulgaria, May 30-31, 1975, Berlin, East Germany, Akademie-Verlag GmbH, 251-253 (1976)

Ryabova, T.Y. and Trukhanov, K.A. "Possibility of Utilizing Electric Fields in Space for Radiation Protection from Protons and Electrons (Protection from Charged Particles Using High Voltage Electric Fields)." in Proceedings of the 6th Annual All-Union Winter School on Space Physics, Part I, 277-278 (1969)

Tooper, R.F. Electrostatic Shielding Feasibility Study [Final Report, June 1961 - Sept. 1962], Wright-Patterson AFB, Ohio, Directorate of Advanced Systems Planning (May 1963)

Townsend, L.W. Galactic Heavy-Ion Shielding Using Electrostatic Fields. NASA Technical Memorandum 86265 (September 1984)

Townsend, L.W. Overview of Active Methods for Shielding Spacecraft from Energetic Radiation. *Physica Medica* (2001) Vol. XVII, Supplement I, 84-85.

Trukhanov, K.A., Ryabova, T. Ya., and Morozov, D. Kh. Active Shielding of Spacecraft. Translated into English from *Aktivnaya Zashchita Kosmicheskikh Korabley,* 1970, by Air Force Systems Command, Wright-Patterson AFB, Ohio, Foreign Technology Division, in AD-742410, (10 March 1972)

Vogler, F.H. "Electrostatic Shielding for Space Vehicles." Institute of Aerospace Sciences, 31st Annual Meeting, New York, NY, Jan. 21-23, 1963, Paper 63-12, see also *AIAA Journal,* 2,872-878 (May 1964)

Vogler, F.H. Analysis of an Electrostatic Shield for Space Vehicles. AIAA *Journal, 2(5),* 872-878 (1964)

Active (Electromagnetic) - Plasma Enhanced

AVCO-Everett Research Lab. Plasma Radiation Shielding, Final Report, Everett, MA, NASA CR-70802 (January 1966)

AVCO-Everett Research Lab. Study of Plasma Radiation Shielding, Quarterly Progress Report, 24 March-23 June 1967, Everett, MA, NASA-CR-86614 (July 1967)

AVCO-Everett Research Lab. Study of Plasma Radiation Shielding, Final Report, Everett, MA, NASA-CR-61640 (May 1968)

Hannah, E.C. "Meteoroid and Cosmic Ray Protection." "Space Manufacturing Facilities (Space Colonies)," Proceedings of the Princeton/AIAA/NASA Conference on Space Colonization, J. Grey, ed., AIAA, (March 1977)

Levy, R.H. and French, F.W. The Plasma Radiation Shield: Concept, and Applications to Space Vehicles. AVCO-Everett Research Lab., Everett, MA, NASA-CR-61176 (9 October 1967)

Levy, R.H. and French, F.W. Plasma Radiation Shield - Concept and Applications to Space Vehicles. *Journal of Spacecraft and Rockets,* 5, 570-577 (May 1968)

Levy, R.H. and French, F.W. The Plasma Radiation Shield: Concept and Applications to Space Vehicles. AVCO-Everett Research Lab., Everett, MA. NASA-CR-61156, AVCO-Everett Research Report-258 (October 1967)

Levy, R.H. and French, F.W. "The Plasma Radiation Shield: Concept and Applications to Space Vehicles." in "Protection Against Space Radiation." A. Reetz, Jr., and K. O'Brien, eds. Proceedings of the Special Sessions on Protection Against Space Radiation, 13th Annual Meeting of the American Nuclear Society, San Diego, CA, June 11-15, 1967. NASA, 1968, 93-187 (1967)

Levy, R.H. and French, F.W. The Plasma Radiation Shield: Concept and Applications to Space Vehicles. AVCO-Everett Research Lab., Everett, MA. NASA-CR-84420, AVCO-Everett Research Report-258 (April 1967)

Levy, R.H. and Janes, G.S. Plasma Radiation Shielding. *AIAA Journal,* 2, 1835-1838 (October 1964)

Levy, R.H. and Janes, G.S., Plasma Radiation Shielding. AVCO-Everett Research Lab, Everett, MA, RR-192, AD-448095 (September 1964)

Levy, R.H. and Janes, G.S. Plasma Radiation Shielding. AVCO-Everett Research Lab, Everett, MA. NASA-CR-71254, AMP-179 (December 1965)

Levy, R.H. and Janes, G.S. Plasma Radiation Shielding for Deep Space Vehicles. *Space/ Aeronautics* 45 (February 1966)

Levy, R.H. and Janes, S. Plasma Radiation Shielding. Proceedings of the 2nd Symposium on Protection Against Radiations in Space, NASA, Washington, 211-215 (1965)

Reitz, J.R. and Milford, F.J. Foundations of Electromagnetic Theory. Addison-Wesley Publishing Co., Reading, MA (1960)

Ryabova, T.Y. "Electrostatic Shielding Against Cosmic Radiation (Current Status and Prospects)." Joint Publications Research Service, Arlington, VA, (translated from *Space Biology and Aerospace Medicine (Kosmich. Biiol. I Aviakosmich. Med)* (Moscow) 17(2),4-7, March-April 1983 (May 1983)

Winglee, R.M., Slough, J., Ziemba, T., and Goodson, A. Mini-magnetospheric Plasma Propulsion: High Speed Propulsion Sailing the Solar Wind. Space Technology and Applications International Forum-2000, M.S. El-Genk, ed., American Institute of Physics CP504,1-56396-9, p. 962, (2000)

Winglee, R.M., Slough, J., Ziemba, T., and Goodson, A. Mini-magnetospheric Plasma Propulsion: Tapping the Energy of the Solar Wind for Spacecraft Propulsion. *Journal of Geophysical Research* (September 2000)

Zubrin, R.M., The Use of Magnetic Sails to Escape from Low Earth Orbit. *Journal of British Interplanetary Society,* 46, *3* (1993)

Active (Electromagnetic) - Local Magnet Coil

Baldwin, A.E., *et. al.* Feasibility of Magnetic Orbital Shielding System. Lockheed Missiles & Space Company, Sunnyvale, CA, AD 483301 (May 1964)

Bernert, R.E. and Stekly, Z.J.J. "Magnetic Radiation Shielding Using Superconducting Coils." Proceedings of the 2nd Symposium on Protection against Radiations in Space. NASA SP-169, 199-209 (1964)

Bernert, R.E. and Stekly, Z.J.J. Magnetic Radiation Shielding Systems Analysis. NASA-CR64915, AMP-134 (July 1964)

Bhattacharjie, A. and Michael, I. Mass and Magnetic Dipole Shielding Against Electrons of the Artificial Radiation Belt. *AMA Journal,* 2, 2198-2201 (December 1964)

Brown, G.V. "Magnetic Radiation Shielding." in "High Magnetic Fields." H. Kolm, B. Lax, F. Bitter, and R. Mills, eds. The MIT Press, Cambridge, MA, 370-378 (1962)

Cambel, A.B. MHD for Spacecraft. *Science Journal,* 69-73 (January 1970)

Dorn, R.V., Jr., and Dorn, G.A. Protecting Humans from Ionizing Radiation in Space. *Analog Science Fiction & Fact,* 111*,* 34-50 (Mid-December 1991)

Dow, N.F. Structural Implications of the Ionizing Radiation in Space. Proceedings of the Manned Space Stations Symposium, Los Angeles, CA (April 20-22, 1960)

Edmonson, N., Verwers, C.D., and Gibbons, F.L. "Shielding of Space Vehicles by Magnetic Fields." in "Atomic Energy Commission, Division of Technical Information, Washington, D.C. Proceedings of the Sum., Gatlinburg, TN, 5-7, 808-818 (1962)

Egglesson, G.A. and Murphy, G. "Superconducting Coils for Shielding in Space." Proceedings of the American Institute for Aeronautics and Astronautics, and American Astronautical Society, Stepping Stones to Mars Meeting, Baltimore, MD, March 28-30, 1966. Technical Papers. AIAA, New York, 282-287 (1966)

Engelberger, J.F. "Space Propulsion System." U.S. Patent Number 3,504,868, Filed November 20, 1963, Issued April 7, 1970

Good, R.C., Shen, S.P., and Dow, N.F. Active Shielding Concepts for the Ionizing Radiation in Space. [Final Report, 1 Sep. 1962-31 Aug. 1963] General Electric Co., Philadelphia, PA; Space Sciences Lab. NASA-CR-58950 (31 January 1964)

Grishin, S.D., Zavadskii, V.A., Ogorodnikov, S.N., and Orlov, R.V. "Experimental Investigation of Magnetic Shields." *Soviet Physics - Technical Physics* 23(3), March 1978, 364-366 (translated into English by D. Parsons from *Zhurnal Tekhnicheskoi Fiziki* 48 [1978] 617-621) (1978)

Helgesen, J.O. and Spagnolo, F.A. "The Motion of a Charged Particle in a Magnetic Field Due to a Finite Solenoid with Application to Solar Radiation Protection." 4th Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Los Angeles, CA, June 27-29, 1966, Paper 66-512 (1966)

Hoag, E.D. and Stekly, Z.J.J. Superconducting Coil Technology. NASA-CR-64915, AMP-134 (July 1964)

Kash, S.W. "Magnetic Space Shields." in "Advances in Plasma Dynamics." American Institute of Aeronautics and Astronautics, and Northwestern University. Proceedings of the 6th Biennial Gas Dynamics Symposium, T.P. Anderson and R.W. Springer, eds., Northwestern University Press, 135-166 (1967)

Kash, S.W. "Magnetic Space Shields." American Institute of Aeronautics and Astronautics, and Northwestern University, Biennial Gas Dynamics Symposium, 6th, Evanston, IL, Aug. 25-27, 1965, Paper 65-629 see also Advances in Plasma Dynamics; American Institute of Aeronautics and Astronautics, and Northwestern University, Biennial Gas Dynamics Symposium, 6th, Evanston, IL, August 25-27, 1965, Proceedings, T.P. Anderson and R.W. Springer, eds., Northwestern University Press, 1967, 135-166 (1965)

Kash, S.W. Minimum Structural Mass for a Magnetic Radiation Shield. *AIAA Journal 1,* 14391441 (June 1963)

Kash, S.W. and Tooper, R.F. Active Shielding for Manned Spacecraft. *Astronautics,* 7, 68-75 (September 1962)

Kash, S.W. and Tooper, R.F. Correction on Active Shielding for Manned Spacecraft. *Astronautics, 43* (January 1963)

Kelm, S. and Odelga, P. "Employment of Superconductors in Spaceflight" [ber Die Anwendung Von Supraleitern Fr Die Raumfahrt], Wissenschaftliche Gesellschaft fr Luft-und Raumfahrt and Deutsche Gesellschaft fr Raketentechnik and Raumfahrtforschung, Jahrestagung, Berlin, West Germany, September 14-18, 1964, see also *Zeitschrift für Flugwissenschaften,* 14, 242-247, May 1966 (1964, 1966)

Kholodov, Yu. A. Space Biology and the Magnetic Field. (Translated into English from *Kosmicheskaya Biologiya I Magnitnoye Pole,* Priroda (Moscow) no. 4, 114-115, 1966, by Air Force Systems Command, Wright-Patterson AFB, Ohio Foreign Technology Division (31 January 1967)

Kroger, H., and Labelle, P. Computer Simulation of a Magnetic Shield in a Realistic Space Environment. *ESA Journal,* 12(4),491-497 (1988)

Lepper, R, and Levine, S.H. "The Quasi-hollow Conductor Magnet as a Space Shield Against Electrons (Magnetic Shield Simulator Study of Quasi-hollow Conductor as a Shield for Small Volume Toroidal Vehicle)." in "Protection Against Space Radiation." A. Reetz, Jr., and K. O'Brien, eds., Proceedings of the Special Sessions on Protection Against Space Radiation, 13th Annual Meeting of the American Nuclear Society, San Diego, CA, June 11-15, 1967, NASA 189-214 (1968)

Levine, S.H., Bhattacharjie, A., and Lepper, R. Forbidden Regions Produced by Parallel Dipoles. *AMA Journal,* 4, 654 (1966)

Levine, S.H. and Lepper, R. "Analogue Studies of Magnetic Shields." 4th Meeting of the American Institute of Aeronautics and Astronautics, Aerospace Sciences Los Angeles, CA, June 27-29, 1966, Paper 66-513, see also *AMA Journal,* 6, 695-701, April 1968 (1966, 1968)

Levine, S.H. and Upper, R. A Study of Charged Particle Motion in Magnetic Radiation Shielding Fields. Final Technical Report. Northrop Corp., Hawthorne, CA, Northrop Corporate Labs. NASA-CR-98074, NCL-68-28R (1968)

Levine, S.H. and Lepper, R. An Active Radiation Shield for Cylindrically Shaped Vehicles. *Journal of Spacecraft and Rockets,* 8, 773-777 (July 1971)

Levy, R.H. Radiation Shielding of Space Vehicles by Means of Superconducting Coils, AVCO Corp., AVCO Everett Div., Res. Lab., Res. Rep. 106 (AFBSD TN 61-7), April 1961. (also in *ARS Journal,* 31 [November 1961] 1568-1570) (1961)

Levy, R.H. Author's Reply to Willinski's Comment on Radiation Shielding of Space Vehicles by Means of Superconducting Coils. *ARS Journal,* 32, 787 (1962)

Levy, R.H. The Prospects for Active Shielding. AVCO-Everett Research Lab., Everett, MA, AMP-94 (November 1962)

Levy, R.H. Comment on 'Mass and Magnetic Dipole Shielding against Electrons of the Artificial Radiation Belt.' AIAA *Journal,* 3, 988-989 (1965)

Manuilov, V.G. Optimum Magnetic Radiation Shields. *Soviet Physics - Technical Physics 12(7),* 892-894 (translated into English from *Zhurnal Tekhnicheskoi Fiziki 37* [July 1967] 1230-1232 (January 1968)

McDonald, P.F. An Annotated Bibliography on Motion of Charged Particles in Magnetic Fields and Magnetic Shielding Against Space Radiation. Brown Engineering Co., Inc., Research Labs, Huntsville, AL, NASA-CR-68657 (November 1965)

Modisette, J.L., Snyder, J.W., and Juday, R.D. "Space Radiation Environment." in "Protection Against Space Radiation." A. Reetz, Jr., and K. O'Brien, eds. Proceedings of the Special Sessions on the Protection Against Space Radiation, 13th Annual Meeting of the American Nuclear Society, San Diego, CA, June 11-15, 1967. NASA, 1-17 (1968)

Molton, P.M. The Protection of Astronauts Against Solar Flares. *Spaceflight,* 13, 220-224 (1971)

Morozov, D. Kh., Riabova, T. Ia., Trukhanov, K.A., Sedin, G.Z., and Tsetlin, V.V. "Some Aspects of Active Shielding Against the Radiation in Space." Proceedings of the International Congress on the Protection Against Accelerator and Space Radiation, Geneva, Switzerland, April 26-30, 1971. Volume 1. Geneva, Organisation Europienne pour la Recherche Nuclaire, 1971, p. 501-507. Discussion, p. 508 (1971)

National Bureau of Standards. The Role of Superconductivity in the Space Program: An Assessment of Present Capabilities and Future Potential. Boulder, Colorado (1978)

Norwood, J.M. and Gibbons, F.L. Studies of Magnetic Shielding and Superconductivity, General Dynamics, Fort Worth, TX, AD-423178 (4 November 1963)

Petrov, A. "The 'Magnetic Walls' of a Cosmic Ship." *Nauchn-Tekhn. Obshchestva* SSSR (Moscow), no. 6, 1964, p. 60-61, see also Air Force Systems Command, Wright-Patterson AFB, Ohio, Foreign Technology Division, AD 661766 (March 31, 1967)

Prescott, A.D., Urban, E.W., and Shelton, R.D. "The Application of the Liouville Theorem to Magnetic Shielding Problems." Proceedings of the 2nd Symposium on Protection Against Radiations in Space, NASA, Washington, DC, 189-198 (1965)

Reetz, A., Jr. and OBrien, K., eds. Protection Against Space Radiation. Proceedings of the Special Sessions on Protection Against Space Radiation. 13th Annual Meeting of the American Nuclear Society, San Diego, CA, 11-15 June 1967. NASA-SP-169 (1968)

Simonsen, L.C., Nealy, J.E., Townsend, L.W., and Wilson, J.W. Space Radiation Shielding for a Martian Habitat. 20th SAE Intersociety Conference on Environmental Systems, Williamsburg, VA, July 9-12, 1990, SAE Paper 901346 (1990)

Stekly, Z.J.J. Magnetic Energy Storage Using Superconducting Coils. AVCO-Everett Research Lab., AMP 102 (January 1963)

Stormer, C. The Polar Aurora. Oxford, Clarendon Press 292 (1959)

Tooper, R.F. and Davies, W.O. Electromagnetic Shielding of Space Vehicles. IAS Paper No. 62156 (June 1962)

Tooper, R.F. Electromagnetic Shielding Feasibility Study. Armour Research Foundation Summary Technical Report on Contract AF 33(616)-8489 (September 1962)

Townsend, L.W. HZE Particle Shielding Using Confined Magnetic Fields. *Journal of Spacecraft and Rockets,* 20, 629-630 (November-December 1983)

Townsend, L.W., Nealy, J.E., Wilson, J.W., and Atwell, W. Large Solar Flare Radiation Shielding Requirements for Manned Interplanetary Missions. *Journal of Spacecraft and Rockets,* 26(2),126-128 (March-April 1989)

Townsend, L.W., Wilson, J.W., Shinn, J.L., Nealy, J.E., and Simonsen, L.C. Radiation Protection Effectiveness of a Proposed Magnetic Shielding Concept for Manned Mars Missions. 20th SAE, Intersociety Conference on Environmental Systems, Williamsburg, VA, July 9-12, 1990, SAE Paper 901343 (1990)

Trukhanov, K.A. and Morozov, D. Kh. Optimization of a Magnetic Radiation Shield. *Soviet Physics - Technical Physics* 15(6), December, 1970, 949-953 (translated into English from *Zhurnal Tekhnicheskoi Fiziki 40* (June 1970) 1229-1235 (December, 1970)

Trukhanov, K.A., Riabova, T. Ia., and Morozov, D. Kh. Active Protection of Space Vehicles *(Aktivnaia Zashchita Kosmicheskikh Korablei),* Moscow, Atomizdat (1970)

Urban, E.W. “Superconducting Magnets for Active Shielding.” in “Radiation Physics Research at Marshall Space Flight Center: Research. Achievements Review,” 3, 13-18, NASA, Marshall Space Flight Center, Huntsville, AL (1969)

Von Braun, W. Will Mighty Magnets Protect Voyagers to the Planets? *Popular Science,* 198, 98100 (January 1969)

Willinski, M.I. Comment on ‘Radiation Shielding of Space Vehicles by Means of Superconducting Coils.’ *ARS Journal,* 32, 787 (1962)

Active (Electromagnetic) - Deployed Magnet Coil

Cocks, F.H. A Deployable High Temperature Superconducting Coil (DHTSC) - A Novel Concept for Producing Magnetic Shields Against Both Solar Flare and Galactic Radiation During Manned Interplanetary Missions. *Journal of the British Interplanetary Society,* 44, 99-102 (March 1991)

Cocks, H. 40 Years of Active Shielding. *Journal of Astronautical Sciences,* 47(165-175) (July-Dec, 1999)

Cocks, J.C., Watkins, S.A., Cocks, F.H., and Sussingham, C. Applications for Deployed High Temperature Superconducting Coils in Spacecraft Engineering: A Review and Analysis. *Journal of the British Interplanetary Society,* 50, 479-484 (1997)

Hilinski, E.J. and Cocks, F.H. Deployed High-temperature Superconducting Coil Magnetic Shield. *Journal of Spacecraft and Rockets,* 31, 342-344 (1994)

Jackson, J.D. Classical Electrodynamics. John Wiley and Sons, New York (1962)

Zubrin, R.M., The Use of Magnetic Sails to Escape from Low Earth Orbit. *Journal of the British Interplanetary Society, 46, 3* (1993)

Zubrin, R.M. and Martin, A. “The Magnetic Sail.” Final

Active (Electromagnetic) - Local Magnet Coil or Deployed Magnet Coil

Herring, J.S. “Magnetic Shielding for Spacecraft.” in “NTSE-92: Nuclear Technologies for Space Exploration, American Nuclear Society,” 738-746 (1992)

Herring, J.S. and Merrill, B.J. “Magnetic Shielding for Interplanetary Spacecraft.” Proceedings of the 28th Space Congress, Cocoa Beach, FL, April 23-26, 1991, Cape Canaveral, FL, Canaveral Council of Technical Societies, 1-30-1-38 (1991)

Landis, G.A. “Magnetic Radiation Shielding - An Idea Whose Time Has Returned?” in “Space Manufacturing 8 - Energy and Materials from Space” Proceedings of the 10th Princeton/AIAA/SSI Conference, Princeton, NJ, May 15-18, 1991. Washington, DC, American Institute of Aeronautics and Astronautics, 383-386 (1991)

Paluszek, M.A. “Magnetic Radiation Shielding for Permanent Space Habitats.” in “The Industrialization of Space” Proceedings of the 23rd Annual Meeting of the American Astronautical Society.” San Francisco, CA, Univelt, Inc., 545-574 (1978)

Large Sail/Shield Concept

Reames, D.V. Proceedings of the 26th Intern. Cosmic Ray Conference, Invited Rapporteur and Highlight Papers, AIP Conf. Proc. 516, eds., B.L. Dingus et al., pp. 289-300 (2000).

Tylka, A.J. "New Insights on Solar Energetic Particles from Wind and ACE," Journal of Geophysical Research (2001) Vol. 106 (A11) p. 25333 - 25352.

Tylka, A.J. Private communication (2000)

Active (Electromagnetic) - Miscellaneous

Anderson, P.C. and Koons, H.C. Spacecraft Charging Anomaly on a Low-altitude Satellite in an Aurora. *Journal of Spacecraft and Rockets,* 33, 734-738 (1996)

Baumann, R.C. The Ariel I Satellite. Proceedings of the Royal Society, Series A 281, 439-445, (October 1964)

Birch, P. Radiation Shields for Ships and Settlements. *Journal of the British Interplanetary Society,* 35, 515-519 (November 1982)

Butler, J.M., Jr. "Mars Missions and Bases-A Recent Look." Proceedings of the 18th Electronics and Aerospace Conference (EASCON), IEEE, NY, Catalogue Number 85CII 2213-7, 211-222 (1985)

Christofilos, N.C. The Argus Experiment. *Journal of Geophysical Research,* 64, 869-875 (August 1959)

English, R.A., Benson, R.E., and Barnes, C.M. Apollo Experience Report - Protection Against Radiation, NASA, Washington DC, NASA TND-7080, 2 (1973)

Eugene, N. Single-event Effects in Avionics. *IEEE Transactions on Nuclear Science* 43, 461-474 (1996)

French, F.W. "Solar Flare Radiation Protection Requirements for Passive and Active Shields." Proceedings of the 7th American Institute of Aeronautics and Astronautics, Aerospace Sciences Meeting, New York, NY, Jan. 20-22, 1969, Paper 69-15, see also *Journal of Spacecraft and Rockets,* 7, 794-800, July 1970. (1969, 1970)

Ganguly, N.K. and Lence, J.T. Shielding Manned Space Vehicles from Space Radiations. *Journal of the British Interplanetary Society,* 15, 110-114 (1961-1962)

Goldhammer, L.J. "Recent Solar Flare Activity and its Effect on In-orbit Solar Arrays." Proceedings of the 21st IEEE Photovoltaic Specialists Conference, 2, 1241-1248 (1990)

Haffner, J.W. “Radiation and Shielding in Space.” in “Nuclear Science and Technology,” Volume 4, New York, Academic Press, Inc. (1967)

Hannah, E.C. “Meteoroid and Cosmic Ray Protection.” “Space Manufacturing Facilities (Space Colonies),” Proceedings of the Princeton/AIAA/NASA Conference on Space Colonization, J. Grey, ed., AIAA, (March 1977)

Hannah, E.C. Radiation Protection for Space Colonies. *Journal of the British Interplanetary Society, 30,* 310-314 (August 1977)

Hawkins, S.R. “A Six-foot Laboratory Superconducting Magnet System for Magnetic Orbital Satellite Shielding.” in “International Advances in Cryogenic Engineering” K.D. Timmerhaus, ed., 10, 124, Sections M-U. Proceedings of the Cryogenic Engineering Conference, University of Pennsylvania, Philadelphia, PA, August 18-21, 1964, Plenum Press, New York (1965)

Johnson, R.D. and Holbrow, C., eds. Space Settlements. A Design Study. NASA, Washington, SP-413 (1977)

Keller, J.W. and Shaeffer, N.M. Radiation Shielding for Space Vehicles. *Elec. Eng*. 79, 10491053 (December 1960)

Killian, J.R., Jr. Sputnik, Scientists and Eisenhower: A Memoir of the First Special Assistant to the President for Science and Technology, MIT Press, 186-191 (1977)

Madey, R., Shielding Against Space Radiation. *Nucleonics,* 56-60 (May 1963)

Marvin, D.C. and Gorney, D.J. Solar Proton Events of 1989 - Effects on Spacecraft Solar Arrays. *Journal of Spacecraft and Rockets,* 28, 713-719 (1991)

Mauldin, J.H. Prospects for Interstellar Travel. San Diego, Univelt, Inc., American Astronautical Society, Science and Technology Series, 80, 196-202 (1992)

Norwood, J.M. “The Combination of Active and Passive Shielding.” in “Protection Against Radiation Hazards in Space” Atomic Energy Commission, Division of Technical Information, Washington, DC, Proceedings of the Symposium, Gatlinburg, TN, November 5-7, 1962, 819-828 (1962)

Pierper, G.F., Williams, D.J., and Frank, L.A. Traac Observations of the Artificial Radiation Belt from the July 9, 1962, Nuclear Detonation. *Journal of Geophysical Research* 68, 635-640 (February 1963)

Robey, D.H. Protecting Against Protons - Charged Particle Hazards to Man in Space. SAE *Journal,* 55-57 (November 1960)

Robey, D.H. Radiation Shield Requirements for Two Large Solar Flares. *Astronautica Acta, 6,* FASC 4, 206-224 (1960)

Shen, S.P. Nuclear Problems in Radiation Shielding in Space. *Astronautica Acta, LX, 212-274. (1963)*

Shea, M.A., Smart, D.F., and McCracken, K.G. *Journal of Geophysical Research, 70,4117 (1965)*

Simonsen, L.C. and Nealy, J.E. Radiation Protection for Human Missions to the Moon and Mars. NASA Technical Paper *3079* (February *1991)*

Singer, S.F. Some Consequences of a Theory of the Radiation Belt. *9*th Annual Congress of the IAF, Amsterdam, (August *26, 1958)*

Stares, P.B. The Militarization of Space. U.S. Policy, 1945-1984*,* Cornell University Press, 107-109 (1985)

Stem, D.P. A Brief History of Magnetospheric Physics Before the Spaceflight Era. *Reviews of Geophysics* 27 103-114 (1989)

Swart, H. Some Problems of Protection from Radiation During Space Flights. III [ber Einige Probleme des Strahlenschutzes bei Kosmischen Flgen. III], *Astronomie and Raumfahrt,* No. *2,* 57-64 (1967)

Taber, A. and Normand, E. Single Event Upset in Avionics. *IEEE Transactions on Nuclear Science,* 40, 120-126 (1993)

Townsend, L.W., Wilson, J.W., and Nealy, J.E. Space Radiation Shielding Strategies and Requirements for Deep Space Missions. SAE Paper 891433, 326-328 (1989)

Van Allen, J.A., Mcllwain, C.E., and Ludwig, G.H. Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field. *Journal of Geophysical Research,* 64, 877-91 (August 1959)

Waddington, C.J. The Hazard of Corpuscular Solar Radiation to Manned Spaceflight. *Journal of the British Interplanetary Society,* 277-280 (1961-1962)

Wilson, R.K. Shielding Problems for Manned Space Missions. *IEEE Transactions on Nuclear Science,* 17-23 (January, 1963)

Wrenn, G.L. Conclusive Evidence for Internal Dielectric Charging Anomalies on Geosynchronous Communications Spacecraft. *Journal of Spacecraft and Rockets,* 32, 514-520 (1995)

Yoshida, S., Ludwig, G.H., and Van Allen, J.A. Distribution of Trapped Radiation in the Geomagnetic Field. *Journal of Geophysical Research,* 65, 807-813 (1960)

Extra-terrestrial - Lunar/Mars Regolith

Simonsen, L.C. Analysis of Lunar and Mars Habitation Modules for the Space Exploration Initiative (SEI). in "Shielding Strategies for Human Space Exploration," NASA CP 3360, p. 4347(1997)

Simonsen, L.C., Schimmerling, W., Wilson, J.W., Thibeault, S.A. Construction Technologies for Lunar Base: Prefabricated Versus *In Situ*. NASA CP 3360, p. 297-326 (1977)

Extra-terrestrial - Comets

Crovisier, J. and Encrenaz, T. Comet Science: The Study of Remnants from the Birth of the Solar System, Cambridge University Press, Cambridge, 192 pp. (2000)

Harvard/Center for Astrophysics web site at: http://cfa-www.harvard.edu/iau/Ephemerides/Comets/

Extra-terrestrial - Asteroids

Marsden, B., Unusual Minor Planets Web-Site at Center for Astrophysics http://cfa-www.harvard.edu/iau/lists/Unusual.html

Rabinowitz, D., Bowell, E., Shoemaker, E., and Muinonen, K. "The Population of Earth Crossing Asteroids," in *Hazards Due to Comets & Asteroids,* T. Gehrels, ed., University of Arizona Press, Tucson, pp. 285-306 (1995)

Extra-terrestrial - Orbital Debris

Wilson, J.W., Miller, J., Konradi, A., and Cucinotta, F.A., eds. Shielding Strategies for Human Space Exploration, NASA Conference Publication 3360, Washington (1997)

National Academy Press. "Orbital Debris: A Technical Assessment", Washington, D.C. (1995) (also available on the National Academy of Sciences' web site http://www.nas.edu/)

National Science and Technology Council Committee on Transportation Research and Development. Interagency Report on Orbital Debris -1995. Office of Science and Technology Policy, Library of Congress Catalog Card No. 95-72164 (1995)

NORAD/Space Command web site at: http://www.stratcom.mil/factsheetshtml/reentryassessment.htm

Materials - Quasi-Crystals

Archambault, P. and Janot, D. Theremal Conductivity of Quasicrystals and Associated Processes. *MRS Bulletin,* 22(11) (November 1997)

Besser, M.F. and Eisenhammer, T. Deposition and Applications of Quasicrystalline Coatings. *MRS Bulletin,* 22(11) (November 1997)

Foster, K., Leisure, R.G., Shaklee, J.B., Kim, J.Y., and Kelton, K.F. Ultrasonic Study of Hydrogen Motion in a Ti-Zr-Ni Icosahedral Quasicrystal and a 1/1 bcc Crystal Approximate. *Physical Review B,* 61, 241-245 (2000)

Jenks, C.J. and Thiel, P.A. Surface Properties of Quasicrystals. *MRS Bulletin,* 22(11) (November 1997)

Kelton, K.F. Ti/Zr-based Quasicrystals - Formation, Structure and Hydrogen Storage Properties. Proceedings of the Materials Research Society Symposium, 533, 471-482 (1999)

Kelton, M.F. and Gibbons, P.C. Hydrogen Storage in Quasicrystals. *MRS Bulletin,* 22(11), 69-72 (November 1997)

Kelton, K.F., Kim, J.Y., Majzoub, E.H., Gibbons, P.C., Viano, A.M., and Stroud, R.M. Hydrogen Storage in a Stable Ti-quasicrystal. International Conference on Quasicrystals, Tokyo, Japan (1997)

Kelton, K.F., Kim, W.J., and Stroud, R.M. A Stable Ti-based Quasicrystal. *Applied Physics Letters,* 70, 3230-3232 (1997)

Kelton, K.F., Viano, A.M., Stroud, R.M., Majzoub, E.H., Gibbons, P.C., Misture, S.T., Goldman, A.I., and Kramer, M.J. Hydrogen Storage in Ti-based Quasicrystals. Proceedings of New Horizons in Quasicrystals, Ames, IA, August 19-23, 1996 (1996)

Kim, J.Y., Gibbons, P.C., and Kelton, K.F. Hydrogenation of Pd-coated Samples of the Ti-Zrbased Icosahedral Phase and Related Crystalline Phases. *Journal of Alloys and Compounds,* 266, 311-317 (1998)

Kim, J.-Y., Gibbons, P.C., and Kelton, K.F. Hydrogen Absorption in $Ti_{45}Zr_{38-x}Ni_{17+X}$ Quasicrystals and Measurements of the Equilibrium Vapor Pressure. *Metals and Materials,* 5(6), 589-592 (1999)

Kim, J.Y., Kim, W.J., Gibbons, P.C., Kelton, K.F., and Yelon, W.B. Neutron Diffraction Determination of Hydrogen Atom Locations in the α(TiCrSiO) 1/1 Crystal Approximant. *Physical Review B,* 60, 1-8 (1999)

Majzoub, E.H., Kim, J.-Y., Hennig, R.G., Gibbons, P.C., Kelton, K.F. and Yelon, W.B. Cluster Structure and Hydrogen in Ti-Zr-Ni Quasicrystals and Approximants. Proceedings of the 7th International Conference on Quasicrystals, Stuttgart, German, September 20-24, 1999 (1999)

Nicula, R., Jianu, A., Biris, A.R., Lupu, D., Manaila, R., Devenyi, A., Kumpf, C., and Burkel, E. Hydrogen Storage in Icosahedral and Related Phases of Rapidly Solidified Ti-Zr-Ni Alloys. *European Physical Journal B,* 3, 1-5 (1998)

Shechtman, D. and Lang, C.I. Quasiperiodic Materials: Discovery and Recent Developments. *MRS Bulletin,* 22 (11) (November 1997)

Sordelet, D.J. and Dubois, eds. Quasicrystals: Perspectives and Potential Applications. *MRS Bulletin,* 22 (11) (November 1997)

Stroud, R.M., Viano, A.M., Gibbons, P.C., Kelton, K.F., and Misture, S.T. Stable Ti-based Quasicrystal Offers Prospect for Improved Hydrogen Storage. *Applied Physics Letters* 69 (20), 2998-3000 (1996)

Tsai, A.P. Metallurgy of Quasicrystals: Alloys and Preparation. *MRS Bulletin,* 22 (11) (November 1997)

Urban, K., Feuerbacher, M., and Wollgarten, M. Mechanical Behavior of Quasicrystals. *MRS Bulletin,* 22 (11) (November 1997)

Viano, A.M., Stroud, R.M., Gibbons, P.C., McDowell, A.F., Conradi, M.S., and Kelton, K.F. Hydrogenation of Titanium-based Quasicrystals. *Physical Review B,* 51, 12026-12029 (1995)

Materials - Hydrogen-Palladium

Fukai, Y. The Metal-Hydrogen System: Basic Bulk Properties. Springer-Verlag (1993)

McLellan, R.B. Diffusion of Hydrogen Through Binary Noble Metal Solid Solutions. Miami International Symposium on Metal-Hydrogen Systems, Miami Beach, FL, April 13-15, 1981 (1981)

Otterson, D.A. and Smith, R.J. Absorption of Hydrogen by Palladium and Electrical Resistivity up to Hydrogen-Palladium Atom Ratios of 0.97. NASA Technical Note, NASA TN D-5441 (September 1969)

Peisl, H. “Lattice Strains Due to Hydrogen in Metals.” in “Hydrogen in Metals, I: Basic Properties. G. Alefeld and J. Völkl, eds. Springer-Verlag (1978)

Smith, D.P. Hydrogen in Metals. The University of Chicago Press (1948) Wise, E.M. Palladium: Recovery, Properties and Uses. Academic Press (1968)

Materials - Hydrides

Sapru, K. Development of Improved Metal Hydride Technology for the Storage of Hydrogen. Final Technical Report, Energy Conversion Devices, Inc. (December 1998)

Sapru, K., Stetson, N., Ming, L., Evans, J., Van Kirk, H., and St. John, G. High Density and Safe Hydrogen Storage for Unmanned Undersea Vehicles and Electric Land Vehicles. R&D Status Report, Energy Conversion Devices, Inc. (1998)

Schwarz, R.B. Hydrogen Storage in Magnesium-Based Alloys. MRS Bulletin, 40-44 (November 1999)

Strickland, G. Hydrogen Storage Technology for Metal Hydrides. Hydrogen for Energy Distribution (July 24-28, 1978)

Terry, R.E. Lithium Hydride Debris Shields for Plasma Radiation Sources. Naval Research Laboratory, NRL/MR/6720-96-7868 (September 1996)

Welch, F.H. Lithium Hydride: A Space Age Shielding Material. *Nuclear Engineering and Design,* 26, 444-460 (1974)

Yang, J., Ciureanu, M., and Roberge, R. Hydrogen Storage Properties of Nano-composites of Mg and Zr-Ni-Cr Alloys. *Materials Letters* 43, 234-239 (2000)

Materials - Pure Hydrogen

Post, J.V. Hydrogen ice spacecraft. AIAA Space Programs and Technologies Conference, Huntsville, AL, September 25-28, 1990 (1990)

Post, J.V. “Unusual Spacecraft Materials.” in “Engineering, Construction and Operations in Space II: Volume 2,” S.W. Johnson and J. P. Wetzel, eds., 1055-1064, Proceedings of Space 90, Albuquerque, NM, April 22-26,1990 (1990)

Materials - Hydrogen Absorbing Carbon Materials

Chambers, A., Park, C., Baker, R.T., and Rodriguez, N.M. Hydrogen Storage in Graphite Nanofibers. *Journal of Physical Chemistry B,* 102, 4254-4256 (1998)

Dillon, A.C., Jones, K.M., Bekkedahl, T.A., Kiang, C.H., Bethune, D.S., and Heben, M.J. Storage of Hydrogen in Single-walled Carbon Nanotubes. *Nature,* 386, 377-379 (1997)

Dresselhaus, M.S., Williams, K.A., and Eklund, P.C. Hydrogen Absorption in Carbon Materials. *MRS Bulletin,* 45-50 (November 1999)

Huffman, D.R. Creation and Destruction of C60 and Other Fullerene Solids. Final Report, Department of Energy, Grant DE-FG03-93ER12133 (June 1996)

Liu, C., Fan, Y.Y., Liu, M., Cong, H.T., Cheng, H.M., and Dresselhaus, M.S. Hydrogen Storage in Single-walled Carbon Nanotubes at Room Temperature. *Science,* 286, 1127-1129 (1999)

Pekala, R. W., Coronado, P. R., and Calef, D. F. Synthesis, Characterization, and Modeling of Hydrogen Storage in Carbon Aerogels. DOE Hydrogen Program Review, Coral Gables, FL, April 19-21, 1995 (1995)

Skolnik, E.G. Technical Evaluation Report on Carbon Nanotubes for Hydrogen Storage as Being Studied by Northeastern University. Energetics, Inc. (August 1997)

Skolnik, E.G. Technical Evaluation Report on Hydrogen Storage in Carbon Nanofibers as Being Studied by Northeastern University. Energetics, Inc. (June 1997)

Tomanek, D. and Enbody, R. J., eds. Science and Application of Nanotubes. Klewer Academic/ Plenum Publishers, New York (2000)

Materials - Polymers

Fedderly, J.J. Experimental Investigation of Various Properties of Polyethylene Filled Polyester (PFP) Neutron Shielding Materials. Naval Surface Weapons Center, NSWC TR-82-392 (1983)

McGarvey, J.W. and Veroeven, W.M. Castable Materials for Neutron Shields. Technical Report, Rock Island Arsenal Laboratory (1961)

Wilson, J.W., Simonsen, L.C., Shinn, J.L., Rubey, R.R., Jordan, W., and Kim, M. Radioactive Analysis for the Human Lunar Return Mission. NASA Technical Paper 3662 (1997)

Materials - Miscellaneous

Jaeger, R.G., Blizard, E.P., Chilton, A.B., Grotenhuis, M., Honig, A., Jaeger, T.A., and Eisenhohr, H.H. Engineering Compendium on Radiation Shielding. Volume II, Shielding Materials. Springer-Verlag (1975)

Kim, M.-H.Y., Thibeault, S.A., Simonsen, L.C., and Wilson, J.W. Comparison of Martian Meteorites and Martian Regolith as Shield Materials for Galactic Cosmic Rays. NASA Technical Publication TP-1998-208724 (October 1998)

Profio, A.E. Radiation Shielding and Dosimetry. John Wiley & Sons (1979)

U.S. Department of Energy. Proceedings of the 1995 U.S. DOE Hydrogen Program Review. Volume II, NREL/CP-430-20036, Coral Gables, FL, (April 18-21, 1995)

U.S. Department of Energy. Proceedings of the 1996 U.S. DOE Hydrogen Program Review. Volume II, NREL/CP-430-21968, Miami, FL, (May 1-2,1996)

U.S. Department of Energy. Proceedings of the 1998 U.S. DOE Hydrogen Program Review. Volume II, NREL/CP-430-21968, Alexandria, VA (April 28-30,1998)

Appendix F

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Acronyms and Units

AU	Astronomical Unit (average Sun-Earth distance)
Coulomb (C)	Unit of electrical charge = $(1.6X10^{-19}$ electron charge$)^{-1}$
ΔV	Initial velocity a spacecraft must achieve to reach another specific destination in space
DOE	Department of Energy
DNA	Deoxyribonucleic Acid
eV e	Kinetic energy achieved when a particle carrying the electrical charge of one electron is accelerated by a potential difference of 1 volt.
Farad	A unit of electrical capacitance such that 1 Coulomb of charge could be stored with a potential of 1 Volt on a capacitor of one Farad
GCR	Galactic Cosmic Ray
Gauss	Gauss, unit of magnetic induction in the centimeter-gram-second system of physical units. 1 gauss = 10^{-4} Tesla
Geostationary Altitude	The altitude of the circular equatorial orbit with a period of one sidereal day. The radius of this orbit is approximately 6.63 Earth radii
GeV	Gigaelectron Volt (the energy a particle carrying the electrical charge of one electron would gain if it fell across a potential difference of one billion electron volts)
GV	This is short for GeV/ec. It is magnetic rigidity in units of momentum per unit charge. The momentum, P, is in units of GeV/c.
HEDS	Human Exploration and Development of Space
Henrys	A unit of the inductance in the rationalized MKS system (= 1 Weber/ampere)
HZE	High-energy (HE), high-mass (HZ) particles
HZETRN	Radiation transport code
ISS	International Space Station
Joules	Unit of energy = $(6.25X10^{18})$ electron volts
kG	One thousand Gauss (1 gauss = 10^{-4}Tesla)
kW	One thousand Watts of power
Kilo-ton	The energy released by the explosion of 1000 tons of TNT. 1 Kiloton = $4.2X10^{12}$ Joules
Law of Biot and Savart	The law of physics that establishes the relationship between the current being carried in a wire and the magnetic field that current generates anywhere outside the wire.
Liouville's Theorem	States that for a non-dissipative Hamiltonian system, phase space density (the area between phase space contours) is constant.
M2P2	Mini-Magnetospheric Plasma Propulsion
MeV	One million electron volts
MSFC	Marshall Space Flight Center
mTorr	1/1000 Torr or $1.3X10^{-6}$ of an atmosphere

MV	Short for MeV/ec, a unit of magnetic rigidity (= 0.001 GV)
NCRP	National Committee on Radiation Protection
Newton	Unit of mechanical force in the rationalized MKS system
NIAC	NASA's Institute of Advanced Concepts
NRC	National Research Council
NSF	National Science Foundation
REM	Roentgen Equivalent Man, an obsolete unit of dose equivalent. It has been replaced by the Sievert. One Sievert = 100 REM.
SEP	Solar Energetic Particle
Stormer's Equation	Describes the radiation shielding effectiveness of a dipole magnetic field
Stormer Theory	Mathematical approach developed by Carl Stormer in 1930s to calculate the motion of a charged particle in a dipole magnetic field.
STS	Space Transportation System
Sv	Sievert is a unit of dose equivalent that measures the biological effectiveness of a radiation dose.
Tesla Field	Standard unit of magnetic field (10^4 Gauss)
Torr	One millimeter of mercury, 1/760 of an atmosphere
TRL	Technology Readiness Level
V	Electric potential in volts
Van der Graaff Machines	Electrostatic particle accelerators that accelerate particles with a large voltage potential.
Wheeler's Approximation	An approximate formula for the magnetic induction of a circular wire loop.
$\left\| \int_L \vec{B} X d\vec{l} \right\|$	The vector cross-product of the magnetic field strength, $\vec{B}$, and a small increment of path length $\vec{dl}$ is integrated along the path a charged particle takes in the magnetic field.

Appendix G

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CURRICULUM VITAE
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PROFESSIONAL SOCIETY MEMBERSHIPS: American Physical Society, American Astronomical Society, American Geophysical Union, Sigma Xi

PUBLICATIONS:

1. The Natural Radiation Environment Inside Spacecraft, IEEE Transactions on Nuclear Science, NS-29, No. 6, pp. 2095-2100, IEEE, Inc., NY, Radiation Effects; 1982.
2. Radiation Doses and Biological Effects of Cosmic Rays, (with C.H. Tsao, R. Silberberg and J.R. Letaw), Proceedings of the 18th International Cosmic Ray Conference, Bangalore, Vol. 2, p. 398, 1983.
3. LET-Distributions and Radiation Doses due to Cosmic Rays (with R. Silberberg, C.H. Tsao and J.R. Letaw), WEE Transactions on Nuclear Science, NS-30, No. 6, p. 4405-8, 1983.
4. Cosmic Ray Transport in the Atmosphere; Dose and LET-Distributions in Materials, (with C.H. Tsao, R. Silberberg and J.R. Letaw), IEEE Transactions on Nuclear Science, NS-30, No. 6, 4398-4, 1983.
5. Radiation Doses and LET-Distributions of Cosmic Rays, (with R. Silberberg, C.H. Tsao and J.R. Letaw), Vol. 98, 209-226, Radiation Research, 1984.
6. LET-Distributions and Doses of HZE Radiation Components at Near-Earth. Orbits, (with R. Silberberg, C.H. Tsao, and John R. Letaw), Adv. in Space Res., 4, 143 (1984).
7. Irradiation of the Moon by Galactic Cosmic Rays and Other Particles (with Maurice M. Shaprio), Proc. of Lunar Bases and Space Activities in the 21st Century, October 29-31, 1984.
8. Radiation Transport of Cosmic Ray Nuclei in Lunar Material and Radiation Doses (with R. Silberberg, C.H. Tsao, and John R. Letaw), Proc. of Lunar Bases and Space Activities in the 21st Century, October 29-31, 1984.
9. LET Spectra in Low Earth Orbit, (with B. Stiller and A. J. Tylka), IEEE Trans. on Nucl. Sci., Vol. 33, 1386-9,1986.
10. "Toward a Descriptive Model of Solar Particles in the Heliosphere", (with M. A. Shea, D. F. Smart, D. Chenette, J. Feynman, C. Hamilton, G. Heckman, A. Konradi, M. A. Lee, D. S. Nachtwey, and E. C. Roleof), Proc. of the Conference on the Interplanetary Particle Environment, JPL Pub. 88-28,3-13, 1988
11. "Toward a Descriptive Model of Galactic Cosmic Rays in the Heliosphere", (with R. A. Mewaldt, A. C. Cummings, P. Evenson, W. Fillius, J.R. Jokipii, R.B. McKibben, and P. A. Robinson), Proc. of the Conference on the Interplanetary Particle Environment, JPL Pub. 88-28, 14-34, 1988
12. "Current Models of the Intensely Ionizing Particle Environment in Space", Proc. of the Conference on the Interplanetary Particle Environment, JPL Pub. 88-28, 49-56, 1988
13. The Absolute Spectra of Galactic Cosmic Rays at Solar Minimum and Their Implications for Manned Spaceflight, (with G. D. Badhwar, R. A. Mewaldt, B. Mitra, P. M. O'Neal, J. F. Ormes, P. Stemwedel and R. E. Streitmatter), 22nd Intl. Cosmic Ray Conference (Dublin), 1991.
14. Report on Constraints on Space Exploration (with no co-authors) Aerospace and Environmental Medicine, Vol. 27, No. 4, P. 7-10,1993.
15. Cosmic Radiation: Constraints on Space Exploration, Nuclear Tracks and Radiation Measurements, Vol. 20,397-401 1991.
16. A Model of the Primary Cosmic Ray Spectra (with J. Lee) Radiation Measurements, Vol. 26, 467-470, 1996.

Biosketch
Dr. Robert A. Cassanova

Education:

North Carolina State University	BS, Aerospace Engineering	1964
University of Tennessee Space Institute	MS, Aerospace Engineering	1967
Georgia Institute of Technology	PhD, Aerospace Engineering	1975

Dr. Cassanova is the Director of the NASA Institute for Advanced Concepts (NIAC) in Atlanta, Georgia. The NIAC is focused on the development of revolutionary, advanced systems and architectures in the fields of aeronautics and space. The NIAC is an independent institute sponsored by NASA. As of May 2000, the NIAC has sponsored the development of 46 revolutionary advanced concepts that could have significant impact on future aeronautics and space systems.

Prior to becoming the Director of NIAC, Dr. Cassanova was Director of the Aerospace and Transportation Laboratory in the Georgia Tech Research Institute (GTRI). The lab performed research in aeronautics, ground transportation, acoustics, materials and structures for the Department of Defense agencies, National Aeronautics and Space Administration, Federal Aviation Administration, Federal Highway Administration, Georgia Department of Transportation, Department of Energy and private industry.

While in GTRI and in the School of Aerospace Engineering at Georgia Tech, he performed research in biofluid mechanics, solar thermal energy, acoustics, combustion and rarefied gas dynamics. His career also includes research in rocket plume testing and high altitude hypersonic flight at the Arnold Engineering Development Center in Tullahoma, Tennessee.

Curriculum Vitae
FRANKLIN HADLEY COCKS

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Professor Cocks received his doctoral degree from MIT in 1965, where he also did his undergraduate work, and was a Fulbright Fellow at Imperial College of Science and Technology, London, in 1966. He is the holder of a NASA Technical Achievement Award for his Development of single crystal beta-alumina membranes for sodium-sulfur battery systems, given in 1974, and launched a successful GAS payload aboard the Shuttle Columbia in 1991. He is a registered United States Patent Agent, holding more than 20 patents. Of his 125 technical papers, some of those most relevant to NASA and the current project are listed below:

"A High Resolution Solar Telescope using Dark-lens Diffractive Optics" (with S. A. Watkins, M. J. Walker, T. A. Lutz and J. C. Sussingham), Solar Physics 198 (2), 211-222 (2001).

"A Dark Lens Diffracting Telescope: Novel Concept for Direct Extrasolar Planet Imaging, (with E. E. Cocks), Optical Engineering, 36, (1997), pp. 2921-2924.

"Forty Years of Development of Active Systems for Radiation Protection of Spacecraft" (with J. Sussingham and S. Watkins), The Journal of the Astronautical Sciences, 47, (1999), pp. 165-175.

"Applications for Deployed High Temperature Superconducting Coils in Spacecraft Engineering: A Review and Analysis" (with J. C. Cocks, S. A. Watkins and C. Sussingham), Journal of The British Interplanetary Society 50, (1997), pp. 479-484.

"Extrasolar Planetary Detection Via Stellar Occultation" (with J. E. Bischoff, S. A. Watkins, K. Higuchi and P. Y. Bely), in Space Telescopes and Instruments, Proceedings of the Society for Photo-optical and Instrument Engineers, 2807, (1996), pp. 34-86.

"A Novel Variable-Gravity Simulation Method: Potential for Astronaut Training," (with J. Sussingham), Aviation Space, and Environmental Medicine 66 (11), (1995) 1094-1096.

"A Deployed High Temperature Superconducting Coil (DHTSC) Magnetic Shield," with E. Hilinski, J. of Spacecraft and Rockets, 31 (1994) 342-344.

"A Deployable High Temperature Superconducting Coil (DHTSC): A Novel Concept for Producing Magnetic Shields Against both Solar Flare and Galactic Radiation during Manned Interplanetary Missions," J. of the British Interplanetary Society, 44 (3), (1991), pp. 99-102.

"Fusing Lunar Materials with Microwave Energy. Part II: Melting of a Simulated Glassy Apollo II Soil," in Lunar and Planetary Science, Vol. XVII, The Lunar and Planetary Institute, Houston, pp. 911-912 (1985), with D.T. Vaniman, T.T. Meek, and A.D. Blake.

"Microwave Processing of Lunar Materials," in Lunar Bases and Space Activities of the 21st Century, ed. by W.W.Mendell, Lunar and Planetary Institute, 1985, 479-486 (with T.T. Meek, D.T. Vaniman, and R.A. Wright).

"Ultralight Reactive Metal Foams in Space: A Novel Concept," J. of Spacecraft and Rockets 21(5) (1984) 510-512.

CURRICULUM VITAE

James H. Derrickson

CURRENT ADDRESS: Space Science Department/SD50, Marshall Space Flight Center, AL, 35812

EDUCATION: B.S., Drexel University, (1967), M.S., University of Arizona, (1978),
Ph.D., University of Alabama in Huntsville, (1983).

POSITIONS: Astrophysicist from 1967 to the present at Marshall Space Flight Center

MEMBERSHIPS: A member of the American Physical Society, Sigma Pi Sigma, and the American Association for the Advancement of Science.

PROFESSIONAL EXPERIENCE:

For the past 28 years, Dr. Derrickson has contributed to the design and development of cosmic ray detectors as part of the MSFC's Cosmic Ray Research Program. Recently the emphasis has been on the measurement of very high energy cosmic rays above 1 TeV/nucleon. The highlights include: the direct measurement of the cosmic ray hydrogen and helium spectra at energies from 2 to 800 TeV ; the further development of the Bristol University Gas Spectrometer 4 (BUGS-4) detector system designed to measure the high energy spectra of the heavy cosmic rays; and the design of a detector system that will use the production of the direct electron-positron pairs by relativistic heavy ions in high-Z targets to measure the energy of the cosmic ray elements silicon to iron in the "knee" region of the "all-particle" energy spectrum.

RECENT SELECTED PUBLICATIONS:

"Cosmic Ray Proton and Helium Spectra - Results from the JACEE Experiment," Ap. J., 502, 278-283, 1998.

"Elemental Abundance of High Energy Cosmic Rays", Nuclear Physics B, 60B, 83-92, 1998.

"A Measurement of the Absolute Energy Spectra of Galactic Cosmic Rays During the 1976-77 Solar Minimum", Nucl. Tracks Radiat. Meas., 20, No. 3, 415-421, 1992. (Ph.D. thesis work)

"Ionizing Radiation Exposure of LDEF* (Pre - Recovery Estimates)", Nucl. Tracks Radiat. Meas., 20, No. 1, 75-100, 1992.

"An Application of the Direct Coulomb Electron Pair Production Process to the Energy Measurement of the 'VH-Group' in the 'Knee' Region of the 'All Particle' Energy Spectrum", 26th ICRC, 5, 65, Salt Lake City, 1999.

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Research Experience:

Dr. Gallagher received the B.S. degree from Iowa State University in 1974, the M.S. degree from the University of Iowa in 1978, and the Ph.D. degree from the University of Iowa in 1982.

Following graduate school he joined the Physics faculty at the University of Alabama in Huntsville where he stayed for two years until leaving the position of Assistant Research Professor in 1984. Since 1984 he has worked in space science for NASA Marshall Space Flight Center. He has worked in a variety of areas including the study of Auroral Kilometric Radiation, Doppler shifted short wavelength ion acoustic waves in the magnetosheath, terrestrial micropulsations, wave-packet bursts upstream of the Jovian bow shock, and dust impacts during transit of the Saturnian ring plane. He has become heavily involved in studying the effects of heavy ions on wave-particle plasma processes and with the empirical modeling of magnetospheric plasmas. In addition, he served as the Study Scientist for the Inner Magnetosphere Imager mission and is a co-investigator on the resulting IMAGE Mission. Most recent work has involved the global, empirical modeling of inner magnetospheric plasmas. Accomplishments include an empirical derivation of plasmaspheric densities as a function of the level of geomagnetic activity in the inner magnetosphere and the on-going development of a new time-dependent model of the plasmasphere, which includes the influences of the ring current and superthermal electron populations.

Selected Publications:

Gallagher, D. L., Short-wavelength electrostatic waves in the Earth's magnetosheath, *J. Geophys. Res.,* 90, 1435-1448, 1985.

Gallagher, D. L., J. D. Menietti, J. L. Burch, A. M. Persoon, J. H. Waite, Jr., and C. R. Chappell, Evidence of high densities and ion outflows in the polar cap during the recovery phase, J. *Geophys. Res.,* 91, 3321-3327, 1986.

Gallagher, D. L., P. D. Craven, R.H. Comfort, and T.E. Moore, On the azimuthal variation of the equatorial plasmapause, *J. Geophys. Res.,* 100, 23,597-23,605, 1995. Gallagher, D. L., P.D. Craven, and R.H. Comfort, A simple model of magnetospheric trough total density, *J. Geophys. Res.,* 103, 9293-9297, 1998.

Gallagher, D. L., P.D. Craven, and R.H. Comfort, Global Core Plasma Model, J. *Geophys. Res.,* 105, 18819-18833, 2000.

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Relevant Publications

1. *Elemental Abundance of High Energy Cosmic Rays, Y.* Takahashi, K. Asakimori, T.H. Burnett, M.L. Cherry, K. Chevli, M.J. Christl, S. Dake, J.H. Derrickson, W.F. Fountain, M. Fuki, J.C. Gregory, R. Holynski, J. Iwai, A. Iyono, W.V. Jones, A. Jurak, M. Kobayashi, J.J. Lord, O. Miyamura, H. Oda, T. Ogata, E.D. Olson, T.A. Parnell, F.E. Roberts, T. Shiina, S.C. Strausz, Y. Takahashi, T. Tominaga, S. Toyoda, J.W. Watts, J.P. Wefel, B. Wilczynski, R.J. Wilkes, W. Wolter, B. Wosiek, H. Yokomi, E.L. Zager, Nuclear Physics B (Proc. Suppl.) 60B, 83-92,1998.
2. *Design and Flight Performance of the Cosmic Ray Detector BUGS-4,* A.E. Smith, J.J. Petruzzo III, J.C. Gregory, C. Thoburn, R.W. Austin, J.H. Derrickson, T.A. Parnell, M.R.W. Masheder, P.H. Fowler, Nucl. Instrum. Meth. Phys. Res., 402(1), 104-122, 1998.
3. *Atmospheric Radioactive Isotopes at Orbital Altitudes,* J.C. Gregory, Radiation Measurements, 26(6), 841850, 1996.
4. *A Measurement of the Absolute Energy Spectra of Galactic Cosmic Rays During the 1976-77 Solar Minimum,* J.H. Derrickson, T.A. Parnell, R.W. Austin, W.J. Selig and J.C. Gregory, Nuclear Tracks and Radiation Measurements, Including Thermoluminescence: International Journal of Radiation Applications and Instrumentation, Part D, 20(3), July 1992.
5. *Energy Spectra of Cosmic Rays above 1 TeV per Nucleon,* T.H. Burnett, S. Dake, J.H. Derrickson, W.F. Fountain, M. Fuki, J.C. Gregory, T. Hayashi, R. Holynski, J. Iwai, W.V.Jones, A. Jurak, J.J. Lord, O. Miyamura, H. Oda, T. Ogata, A. Olsezski, T.A. Parnell, F.E. Roberts, S. Strausz, T.Tabuki, Y. Takahashi T.Tominaga, J.W. Watts, J.P. Wefel, B. Wilczynska, R.J. Wilkes, W. Wolter, and B. Wosiek, Astrophysical Journal 349, L25, 1990.
6. *Reaction of 5eV Oxygen Atoms with Polymeric and Carbon Surfaces in Earth Orbit,* J.C. Gregory, and P.N. Peters, Polymer Preprints, 28(2), 459, American Chemical Society, 1987.
7. *Measurements of Background Gamma-Radiation on Spacelab 2,* G.J. Fishman, J.C. Gregory and W.S. Paciesas, Advances in Space Research 7, 231, 1987.
8. *The Measured Radiation Environment within Spacelabs 1 and 2 and Comparison with Predictions,* T.A. Parnell, J.W.Watts, G.J. Fishman, E.V. Benson, A.L. Frank and J.C. Gregory, Advances in Space Research 7, 1098, 1987.
9. *Cosmic Ray Results from the JACEE Experiment,* T.H. Burnett, J.C. Gregory, T. Hayashi, Y. Takahashi, et. al. (The JACEE Collaboration) Nuclear Physics A461, 263, 1987.

Richard N. Grugel - Biographic Sketch

Richard N. Grugel earned a B.A. in Geological Sciences (1976) and an M.S. in Metallurgical Engineering (1980), both from the University of Wisconsin-Milwaukee. In 1983 he completed a thesis entitled "Solidification, Phase Equilibria, and Structural Transitions in Systems Containing a Liquid Miscibility Gap" and was awarded a Ph.D. in Metallurgical Engineering from Michigan Technological University. This was followed by post-doctoral positions at the Swiss Federal Institute of Technology in Lausanne and at Northwestern Polytechnical University in Xian, People's Republic of China. In 1987 he accepted a position in Vanderbilt University's "Center for the Space Processing of Engineering Materials" as a Research Assistant Professor and in 1990 joined Vanderbilt's "Center for Microgravity Research and Applications". In 1992 he was promoted to Research Associate Professor. In July 1994 Grugel accepted a Staff Scientist position with the Universities Space Research Association and conducted research as an on-site contractor in the Space Sciences Laboratory of the Marshall Space Flight Center. In August 1999 Grugel accepted a Scientist position with Marshall Space Flight Center, Science Directorate.

Grugel has some 20 years experience in solidification processing, particularly in utilizing controlled directional solidification techniques. He has authored or co-authored studies on monotectic, eutectic, dendritic, and composite solidification, both in metal alloys and in transparent, analogous systems. His work since 1987 has given him considerable appreciation of gravity, *or lack of,* as a solidification-processing variable.

<u>Selected Publications</u>

1. R.N. Grugel and A. Hellawell: Alloy Solidification in Systems Containing a Liquid Miscibility Gap, *Metallurgical Transactions A.,* 1981, vol. 12A, p. 669.
2. R.N. Grugel and W.Kurz: Growth of Interdendritic Eutectic in Directionally Solidified Al-Si Alloys, *Metallurgical Transactions A,* 1987, vol. 18A, p. 1137-1142.
3. R.N. Grugel and Y. Zhou: Primary Dendrite Arm Spacing and the Effect of Off-Axis Heat Flow, *Metallurgical Transactions A,* 1989, Vol. 20 A, pp. 969-973.
4. R.N. Grugel: Mixed Gravity Mode Growth During Directional Dendritic Solidification Aboard the KC-135, *Metallurgical Transactions A,* 1989, vol. 20A, pp. 1284-1286.
5. R.N. Grugel: Composite Growth in Hypermonotectic Alloys, *Metallurgical Transactions B,* 1991, vol. 22B, pp.339-348.
6. R.N. Grugel: "Evaluation of <u>Primary</u> Dendrite Trunk Diameters in Directionally Solidified Al-Si Alloys." *Materials Characterization,* 1992, vol.28, pp. 213-219.
7. R.N. Grugel, Shinwoo Kim, Tracey Woodward, and T.G. Wang: "The Effect of Crucible Rotation on Microstructural Uniformity during Horizontal Directional Solidification." *Journal of Crystal Growth,*1992, vol. 121, pp. 599-607.
8. Fay Hua and R.N. Grugel: "Microstructural Development in Undercooled Lead-Tin Eutectic Alloys." *Metallurgical and Materials Transactions,* 1995, vol. 26A, pp. 2699-2706.
9. R.N. Grugel and L.N. Brush: "Observation of Macrosegregation in Directionally Solidified Dendritic Alloys", *Journal of Metals,* 1997, vol. 49, no. 3, pp. 26-30, Invited.
10. R.N. Grugel: "Uniform Composite in a Hypermonotectic Alloy System and Method for Producing the Same," U.S. Patent No. 5,246,508, September 1993.

DAVID H. HATHAWAY

CURRICULUM VITAE (10/13/99)

EDUCATION:

Ph.D., Astrophysics, University of Colorado, 1979.
M.S., Physics, University of Colorado, 1975.
B.S., Astronomy, University of Massachusetts, 1973.

AWARDS AND HONORS:

NASA/MSFC Outstanding Performance Awards, 1986, 1988, 1990, 1994, 1995, 1996. NASA/MSFC Director's Commendation 2000
NASA Certificates of Appreciation, 1986, 1988, 1990, 1991, 1992, 1995, 1998.
NASA Group Achievement Awards, 1992, 1996, 1997.
NSF Fellowships, Honorable Mention, 1973.
Massachusetts Senatorial Honor Scholarships, 1969, 1970, 1971, 1972.
Phi Beta Kappa Membership, 1973.
University of Massachusetts Freshman Physics Award, 1970.

PROFESSIONAL SOCIETIES:

American Astronomical Society (1976-Present)
- Solar Physics Division, AAS (1987-Present)
  - Vice-Chairperson (1991-1992)
  - SPD Committee (1992-1994)
  - Secretary (1988-1991)
  - Media Liaison (1990-1996)
  - Nominating Committee Chair (1992)
- Division for Planetary Sciences, AAS (1981-present)

American Geophysical Union (1997-Present)
International Astronomical Union (1984-Present)
Sigma Xi (1984-Present)

AUTHOR: over 100 articles in professional journals and popular magazines. Recent papers include:

Hathaway, D. H., Beck, J. G., Bogart, R. S., Bachmann, K. T., Khatri, G., Pettito, J. M., Han, S., and Raymond, J.: 2000, "The Photospheric Convection Spectrum," *Solar Phys.* 193, 299.
Hathaway, D. H., Wilson, R. M., and Reichmann, E. J.: 1999, "A synthesis of solar cycle prediction techniques," J. *Geophys. Res. 104,* 22,375-22,388.
Hathaway, D., Gilman, P., Harvey, J., Hill, F., Howard, R., Jones, H., Kasher, J., Leibacher, J., Pintar, J., and Simon, G.: 1996. "GONG Observations of Solar Surface Flows," *Science 272,* 1306-1309.
Hathaway, D. H.: 1996, "Doppler Measurements of the Sun's Meridional Flow," *Astrophys. J.* 460, 1027-1033. Hathaway, D. H.: 1994, "Producing The Solar Dynamo," *EOS, Trans. A. G. U.* 75, 548.
Hathaway, D. H., Wilson, R. M., and Reichmann, E. J.: 1994, "The Shape of the Sunspot Cycle," *Solar Phys.* 151, 177.

INVENTOR: VISAR - Video Image Stabilization And Registration with Paul Meyer.

CURRENT POSITION:

Group Leader: Solar Physics Group, Space Science Department, Science Directorate, National Aeronautics and Space Administration, Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812. Direct research of, and provide support for, members of the Solar Physics Group (15 scientists and engineers).

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Michael J. Heben graduated from John Carroll University in 1984 with a Bachelors Degree in Physics, from Stanford University in 1986 with a Masters Degree in Materials Science and Engineering, and from California Institute of Technology in 1990 with a Doctorate in Chemistry. Dr. Heben performed research in the Photochemistry Group at the Standard Oil Company of Ohio, and with the Research Fabrication Group at the Xerox Palo Alto Research Center prior to seeking graduate degrees. His doctoral thesis developed scanning tunneling microscope techniques for *in situ* investigations of electrode/electrolyte interfaces. Dr. Heben was awarded a National Research Council Postdoctoral Fellowship to perform work at the Naval Research Laboratory, but instead opted to join NREL in 1990 as a postdoctoral associate with A.J. Nozik. With Nozik, he performed experiments to probe hot-electron dynamics in low-dimensional semiconductor structures. He became a Staff Member at NREL in 1992 and developed plasma-based oxidation methods for producing stable light-emitting porous silicon. He was promoted to Senior Scientist in 1996 due to his work on hydrogen storage materials. He is an expert in the application of scanning probe microscopies, synthetic methods for producing layered nanostructured materials, performing electrical transport measurements, and in the study of molecular diffusion and adsorption in environments with reduced dimensionality. He pioneered the use of carbon single wall nanotubes for use in hydrogen storage applications and has focused on the synthesis of carbon nanotube materials using a variety of methods. His group's work on hydrogen storage in carbon nanotubes was named by Discover Magazine as one of the 100 most important scientific discoveries of 1997. He is an International Energy Agency expert for hydrogen storage in IEA Annex 12. He currently leads a group of six that is active in research topics such as hydrogen storage, synthesis and purification of carbon nanotubes, lithium battery, ultracapacitor, and fuel cell materials, and natural gas purification membranes. The group is presently funded by various sources including DOE/OER, DOE/EE, Honda R&D Americas, and NREL's FIRST Program. Heben has co-authored approximately 45 peer-reviewed publications.

Some Publications of Relevance:

1. A.C. Dillon, T. Gennett, K.M. Kones, J.L. Alleman, P.A. Parilla, and M.J. Heben, "A simple and complete purification of single-walled carbon nanotube materials", Adv. Mater., 11(16), 1354-1358,1999.
2. A.C. Dillon, P.A. Parilla, J.L. Alleman, J.D. Perkins, and M.J. Heben, "Controlling single-wall nanotube diameters with variation in laser pulse power", Chem. Phys. Lett., 316, 13-18, 2000.
3. T. Gennett, A.C. Dillon, J.L. Alleman, K.M. Jones, F.S. Hasoon, and M. J. Heben, "Formation of single-wall carbon nanotube superbundles", Chemistry of Materials, 2000.
4. A.C. Dillon, K.M. Jones, T.A. Bekkedahl, C.H. Kiang, D.S. Bethune, and M.J. Heben, "Storage Of Hydrogen In Single-Walled Carbon Nanotubes", Nature 386,377-279 (1997).

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Kent Joosten has worked at the NASA Johnson Space Center in Houston, Texas for the past 20 years after receiving his Masters Degree in Aerospace Engineering from Iowa State University. He began work as a Space Shuttle flight designer and mission analyst, and in addition to helping develop modifications to the Shuttle Orbiter's guidance and navigation flight design characteristics, he served in the Mission Control Center for 28 Space Shuttle missions. Following the Challenger accident, Mr. Joosten led a team dedicated to the development of astronaut procedures and Mission Control computer software to enhance the Shuttle's contingency flight characteristics.

Since 1990, Mr. Joosten has developed operational profiles and flight test plans for the X-38 technology demonstration vehicle, and has participated in developing broad-based strategies for the future human exploration of the moon and Mars. In his current role as the Chief Engineer in NASA's Exploration Office, he is charged with coordinating technology plans, demonstration projects, and robotic mission payloads which will prepare the way for human missions of exploration to other planets in our solar system.

Some Publications of Relevance:

"Continuing Development of the NASA Human Mars Mission Design", B . Kent Joosten, Jeff George, Gerald *Condon* and Stephen J. Hoffman, The Sixth International Conference and Exposition on Engineering, Construction, and Operations in Space, Albuquerque, NM, April 26-30, 1998.

"Preparing for Human Exploration", Bret G. Drake and B. Kent Joosten, The Sixth International Conference and Exposition on Engineering, Construction, and Operations in Space, Albuquerque, NM, April 26-30, 1998.

"Early Lunar Resource Utilization: A Key to Human Exploration", B. Kent Joosten and Lisa A. Guerra, AIAA Space Programs, and Technologies Conference and Exhibit, Huntsville, AL, September 21-23, 1993. (AIAA 93-4784)

"Mission Design Strategies for the Human Exploration of Mars", B.K. Joosten, B.G. Drake, D.B. Weaver, J.K. Soldner, 42nd Annual Astronautical Conference, Montreal, Canada, Oct 5-11, 1991. (IAF 91-336)

"Mars Trajectory Options for the Space Exploration Initiative", J.K. Soldner, B.K. Joosten, AAS/AIAA Astrodynamics Conference, Durango, CO, Aug. 19-22, 1991. (AAS 91-438)

CURRICULUM VITAE

William H. Kinard
Senior Research Scientist
NASA / Langley Research Center

Since entering on duty with the NACA at the Langley Research Center in 1955, his career with the NACA and later with NASA has focused on research to define the meteoroid and the manmade debris environments in space and the effects these environments can have on operational spacecraft.

Dr. Kinard conceived and was Principle Investigator for the Interplanetary Micrometeoroid Experiments on the Pioneer 10 and 11 spacecraft that first measured the populations of micrometeoroids in the asteroid belt and near Jupiter and Saturn and that also first established that micrometeoroids in the asteroid belt and near the outer planets would present no significant hazard to follow-on spacecraft exploring these and the other outer planets.

He conceived and was Principle Investigator for the Meteoroid Technology Satellite, which first demonstrated in space that the "Meteor Bumper Shield" is an effective concept to shield against impacting meteoroids and orbiting debris. Bumpers are now used to shield most large spacecraft including the International Space Station.

He also conceived, managed the design and development, and later was Chief Scientist for the Long Duration Exposure Facility (LDEF) which obtained a treasure trove of information on the environments (including natural meteoroid and man-made orbiting debris) in near Earth space and the effects of these environments on spacecraft. The LDEF data set is now regarded as the "benchmark" for environmental effects on spacecraft in LEO.

Dr. Kinard has written more than 200 technical publications; he has 8 Patents for space related inventions; numerous awards including the NASA Medal for Exceptional Scientific Achievement and an Honorary Doctors degree from Clemson University. He is currently working on space environmental effects experiments to be performed on the International Space Station.

Brief Resume - Stephen H. Knowles

Knowles received his B.A. from Amherst College in June 1961, and his Ph.D from Yale University in June 1968, with specialization in celestial mechanics.

He was employed by the Naval Research laboratory from 1961 to 1986 as a research scientist in the Radio Astronomy Branch of the Space Science Division. His work there included pioneering contributions to radar astronomy, spectral line radio astronomy and very long baseline interferometry. Notable achievements included his thesis, “A Determination of the Astronomical Unit from Hydrogen Line Radial Velocity Measurements”, which resolved a discrepancy in measurements of the size of the Earth’s orbit, and participation with Charles Townes’ group in the discovery of water vapor masers. He was awarded a two-year sabbatical fellowship at the C.S.I.R.O. in Australia, where he led the first investigations of southern hemisphere water vapor masers. He also published in the field of ionospheric research. Knowles was a three time recipient of NRL’s Research Publication Award.

From 1986 to 1996 Knowles was Technical Director of the Naval Space Surveillance Center, where he led in the application of space environmental knowledge to operational orbit determination. He served as the navy’s primary expert in the fields of space surveillance, extraterrestrial radar, orbital mechanics and the space environment, including space debris. He was awarded the Navy’s Meritorious Civilian Service Medal.

After retiring from Federal service, Knowles has been employed by the Raytheon Corporation as a Chief Scientist with full-time duty at the Naval Research Laboratory.

Knowles has published over 80 papers in refereed journals. Recent examples of his work include:

“A search for small comets with the Naval Space Command radar”, S. Knowles, R.R. Meier, A.S. Gustafson, and F.J. Giovane, J.G.R. 104, A6, pp. 12637-12643, June 1, 1999 and participation in the National Research Council’s Committee on Space Debris, which published the report

“Orbital Debris - A Technical Assessment”, National Academy Press, Wash., DC 1995 - Knowles was a member of the National Academy of Sciences committee that prepared this report.

Larry Kos
Curriculum Vitae

Larry Kos has been the Lead Engineer on the Human Mars Mission Study for the Advanced Concepts Department (ACD) in the Space Transportation Directorate (previously the Preliminary Design Office in the Program Development Directorate) since 1996. He is a co-lead on the intercenter Trajectory Team, which was put in place to facilitate all efforts in the REDS arena. He was also the technical point of contact for the intercenter Integrated Human Mars Mission Study activity. Current assignments include functioning as the ACD Technical Lead for 3rd & 4th Generation In-space Transportation and supporting all Decadal Planning activities. This DPT support includes membership and involvement in the Transportation Systems Team (1- 2 individuals from each NASA center involved in in-space transportation), the Architectures Team (focused activity on leading architectures), and the Propellant Aggregation Team. The support for each of these teams required running varied mission, trajectory, sizing, and orbital analyses as well as daily intercenter coordination and interfacing.

He has worked in the mission analysis and orbit mechanics areas since 1991, selecting orbits and modeling missions for projects including the Magnetosphere Imager (Ml), Laser Atmospheric Wind Sounder (LAWS), Advanced X-ray Astrophysics Facility - Spectrometer (AXAF-S), Space Station Redesign, Cargo Transfer and Return Vehicle (CTRV), QuickSat, Quick LAWS, and the Autonomous Earth Orbiting LIDAR Utility Sensor (AEOLUS) studies. He also worked the Solar Thermal Upper Stage (STUS) and was co-lead engineer for that study. Recent studies include the Back To The Moon study, Beyond LEO Advanced Space Transportation (BLAST) study, and again was co-lead for the Human Lunar Return (HLR) Study.

His professional background also includes over 18 years of work in the field of dynamics, with specific applications in the areas of astrodynamics (orbital mechanics, mission design and trajectory / orbit selection, mission modeling, etc.) and structural dynamics (analyses and modeling). He began his NASA career in 1982 in the Systems Dynamics Laboratory, Structural Dynamics Division.

He obtained a B.S. in Aerospace Engineering from University of Colorado in 1982, and more recently, an M.A.E. in Aerospace Engineering from Auburn University in 1996. He has completed all coursework and exams for the doctorate in aerospace engineering (at Auburn also), and has commenced and is continuing to work on the research for the dissertation. The topic is in the field of advanced mission design and trajectory selection.

Thomas A. Parnell

Astrophysicist, University of Alabama at Huntsville

EDUCATION: Ph.D., Physics, U. North Carolina, 1965

PROFESSIONAL EXPERIENCE:

1966-67	Assistant Professor, Physics, Marshall U.
1967-68	Astrophysicist, MSFC/NASA
1968-1999	Astrophysicist Branch Chief, MSFC/NASA
1999-present	Adjunct Professor, Univ. of Ala., Huntsville

SPECIAL ASSIGNMENTS: Project Scientist, HEAO 3,1970-84
Principal Investigator, Spacelab 1 and 2, 1977-85
Member, Space Station Environments Panel, 1985-1999
Chairman, LDEF Special Investigation Group, 1989-1993
Chairman, SEE Technical Working Group, 1993-1999

PROFESSIONAL SOCIETIES: American Physical Society, Sigma Xi

Publications

1 . Benton, E. V., D. D. Peterson, J. V. Bailey, and T. A. Parnell, “High-LET Particle Exposure of Skylab Astronauts,” Journal of Health Physics, 32, 15 (1977).
2. Benton, E. V., T. A. Parnell, et al., “Radiation Measurements Aboard Spacelab 1,” Science, 225, 224-225 (1984).
3. Akopova, A. B., N. V. Magradze, V. E. Dudkin, E. E. Kovalev, Yu. V. Potapov, E. V. Benton, A. L. Frank, E. R. Benton, T. A. Parnell, and J. W. Watts, Jr., “Linear Energy Transfer (LET) Spectra of Cosmic Radiation in Low Earth Orbit,” Nucl. Tracks & Radiat. Meas., 17(2),93-97 (1990).
4. Akatov, Yu. A., V. E. Dudkin, E. E. Kovalev, E. V. Benton, A. L. Frank, J. W. Watts, Jr., and T. A. Parnell, “Depth Distribution of Absorbed Dose on the External Surface of Cosmoc 1887 Biosatellite,” Nucl. Tracks & Radiat. Meas., 17(2), 105-107 (1990).
5. Harmon, B.A., G. J. Fishman, T. A. Parnell, E. V. Benton, and A. L. Frank, “LDEF Radiation Measurements: Preliminary Results,” Nucl. Tracks Radiat. Meas., 20(1), 131-136 (1992).
6. Dudkin, V. E., E. E. Kovalev, Yu. V. Potapov, E. V. Benton, A. L. Frank, E. R. Benton, J. W. Watts, Jr., T. A. Parnell, E. Schopper, B. Baican, G. Reitz, H. Bucker, R. Facius, R. Beaujean, and C. Heilmann, “Cosmic Ray LET Spectra and Doses Onboard Cosmos-2044 Biosatellite,” Nucl. Tracks Radiat. Meas., 20(1), 149-155 (1992).
7. Derrickson, J. H., T. A. Parnell, R. W. Austin, W. J. Selig, and J. C. Gregory, “A Measurement of the Absolute Energy Spectra of Galactic Cosmic Rays During the 1976-77 Solar Minimum,” Nucl. Tracks Radiat. Meas., 20(3),415-421 (1992).
8. Benton, E. V., T. A. Parnell, J. H. Derrickson, G. J. Fishman, J. W. Watts, et al., “Ionizing Radiation Exposure of LDEF (Pre-Recovery Estimates),” Nucl. Tracks Radiat. Meas., 20(1), 75-100 (1992).

Dr. Bruce A. Remington

PRESENT POSITION: Hydrodynamics Group Leader, NIF Program, LLNL
Address: L-02 1, LLNL, CA 94550
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PERSONAL: U.S. citizen, Q-cleared

PROFESSIONAL MEMBERSHIPS: American Physical Society
American Astronomical Society

EDUCATION:
Ph.D. in Physics from Michigan State University, East Lansing, MI (1986); nuclear physics.
B.S. in Mathematics from Northern Michigan University, Marquette, MI (1975).

PREVIOUS RESEARCH EXPERIENCE:
(1995-present): Group Leader for Hydrodynamics, ICF program, LLNL: Initiate, lead, manage experiments in hydrodynamics related to ICF, high energy-density regimes, compressed solid state regimes, fluid dynamics, astrophysics. Lead, manage 2 LDRD-ER grants, and 3 University Use of Nova initiatives.
(1988-1995): Physicist, Laser Experiments and Advanced Diagnostics, ICF program, LLNL: Implosion experiments, hydrodynamic instabilities experiments, numerical simulations. Led, supervised Wolter x-ray calibration facility. (1986-1988): Postdoctoral research associate at LLNL in experimental heavy-ion nuclear physics and in preequilibrium reactions modeling and experiments.

HONORS: 1995 American Physical Society Excellence in Plasma Physics Award.
Fellow of the American Physical Society.

GENERAL RESEARCH INTERESTS:
Hydrodynamics, high energy-density physics, solid-state physics, astrophysics

PUBLICATIONS AND OTHER PAPERS:
1. "Modeling astrophysical phenomena in the laboratory with intense lasers," B.A. Remington, D. Arnett, R.P. Drake, and H. Takabe, Science 284, 1488 (28 May 1999).
2. *"The Evolution of High energy-density physics: from nuclear testing to the superlasers,"* E.M. Campbell, N.C. Holmes, S.B. Libby, B.A. Remington, and Edward Teller, Laser and Particle Beams 15, 607-626 (1997).
3. *"Supernova hydrodynamics on the Nova laser,"* B.A. Remington *et al.,* Phys. Plasmas 4, 1994 (1997).
4. *"Supernova-relevant hydrodynamic instability experiments on the Nova laser," J.* Kane *et al.,* Astrophysical Journal 478, L75 (1997).
5. "Scaling supernova hydrodynamics to the laboratory," J. Kane *et al.,* Phys. Plasmas 6, 2065 (1999).
6. *"Bringing the stars down to earth,"* James Glanz, Science 276, 351 (1997).
7. *"Measurement of 0.35* ***m*** *laser imprint in a thin Si foil using an x-ray laser backlighter,"* D.H. Kalantar *et al.,* Physical Review Letters 76, 3574 (1996).
8. *"3D single mode Rayleigh-Taylor experiments on Nova"* M.M. Marinak *et al.,* Physical Review Letters 75, 3677 (1995).
9. *"Multimode Rayleigh-Taylor experiments on Nova,"* B.A. Remington *et al.,* Physical Review Letters 73, 545 (1994).
10. *"Large growth Rayleigh-Taylor experiments using shaped laser pulses,"* B.A Remington *et al.,* Physical Review Letters 67, 3259 (1991).

L. W. Townsend, Ph.D.

Biographical Information: Dr. Townsend began his professional career with the U. S. Navy as a nuclear submarine engineering officer. In 1977 he left the U. S. Navy to pursue studies at the University of Idaho where he was awarded a Ph.D. in theoretical nuclear physics in 1980. In January 1981 he accepted a U. S. Civil Service position as a Research Scientist in the Space Systems Division at NASA Langley Research Center, where he remained until leaving NASA as a Senior Research Scientist in 1995. While at NASA he served as PI and research project manager for the Langley space radiation group in the areas of space radiation interactions, transport, shielding and risk assessment. He also received numerous scientific awards including NASA's highest research honor - a NASA Exceptional Scientific Achievement Medal for outstanding contributions to the understanding of nuclear interactions of cosmic radiation with matter and its implications for space radiation exposure and shielding. Dr. Townsend joined the faculty at The University of Tennessee Department of Nuclear Engineering in 1995. He teaches graduate courses in Space Radiation Protection (NE 621), Neutron Science and Engineering Applications (NE 697), Charged Particle Transport and Interactions (NE 621) and in Radiation Protection (NE 551). He also teaches undergraduate courses in the Nuclear Fuel Cycle (NE 404), Nuclear Systems Design (NE472) and Nuclear Reactor Theory (NE 470). He currently supervises the research of 4 Ph.D. students and 4 M.S. students. He received the Leon and Nancy Cole Superior Teaching Award from the UTK College of Engineering in 1999 and has twice been selected by the NE undergraduate students as Professor of the Year (1996 and 2000). Dr. Townsend is a NCRP Council Member, chair of NCRP SC 1-7 (Information Needed to Make Radiation Protection for Travel Beyond Low-Earth Orbit) and a member of NCRP SC75 (Guidance on Radiation Received in Space Activities). He is a member of the NIOSH/FAA Flight Attendants Exposure Study Peer Review Panel and is also a current and past member of several NASA panels on space radiation risk assessment. He is the author or coauthor of nearly 400 research publications including over 100 articles in refereed scientific and engineering journals.

Relevant Research Publications

1. Zapp, E. N.; Ramsey, C. R.; Townsend, L. W.; and Badhwar, G. D.: Solar Particle Event Dose and Dose Rate Distributions: Parameterization of Dose-Time Profiles With Subsequent Dose-Rate Analysis. Radiation Measurements, Vol. 30, No. 3, June 1999, pp. 337-343.
2. Townsend, L.W.: HZE Particle Shielding Using Confined Magnetic Fields. Journal of Spacecraft and Rockets, Vol. 20, No. 6, November/December 1983, pp 629-630.
3. Parsons, Jennifer L. and Townsend, Lawrence W.: Interplanetary Crew Dose Rates for the August 1972 Solar Particle Event. Radiation Research, Vol. 153, June 2000, pp.729-733.
4. Townsend, L. W.: Overview of Active Methods for Shielding Spacecraft from Energetic Space Radiation. Physica Medica (submitted).
5. Townsend, L.W.; Wilson, J.W.; Shinn, J.L.; Nealy, J.E.; and Simonsen, L.C.: Radiation Protection Effectiveness of a Proposed Magnetic Shielding Concept for a Manned Mars Mission. 20th Annual International Conference on Environmental Systems (ICES), Williamsburg, Virginia, July 9-12, 1990. SAE Paper No. 901343.

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Education:

1966	B. S. in Physics, Mississippi State University
1972	M. S. in Physics, University of Alabama in Huntsville

Position:

1962-pres.	Physicist, Space Science Department, Marshall Space Flight Center, Huntsville, Alabama

Principal Duties: Perform research modeling the transport of high-energy particles in cosmic ray detectors, and the space radiation environment effects on spacecraft systems. Support MSFC projects by defining the expected space radiation exposure and its' effects. He led the definition of the ionizing radiation environment requirements for the Space Station Freedom and is presently the technical lead on the ionizing radiation environment for International Space Station. He developed the directional proton flux model used to analyze the LDEF radiation experiment results and was in the group that made the model prediction for comparison with the experimental results.

Selected Journal Articles:

Takahashi Y., J.C. Gregory, J. W. Watts, "Multiplicity and Rapidity Distributions in 200 GeV/amu 0 + Pb and S + Pb Interactions from CERN EMU05 Experiments," ibid., vol. 8, p.103

Asakimori K., T.H.Burnett, J. W. Watts," Energy Spectra of Protons and Helium Nuclei above 5 TeV/Nucleon," in 22nd International Cosmic Ray Conference, Conference Papers, vol. 2, p. 97-99, Dublin, Ireland, Aug. 11-23,1991

Asakimori K., T.H.Burnett, J. W. Watts," Spectra, Composition, and Interactions of Nuclei with a Balloon-Borne Superconducting Magnet," ibid., vol. 2, p. 567-570

Takahashi Y., J.C. Gregory, J. W. Watts, "A study of Isospin Clustering and Intermittency Fluctuations in 6.4 TeV S + Pb Interactions from CERN EMU05 Experiments," ibid., vol. 4, p.5-8

Asakimori K., J. W. Watts, "Energy Spectra and Composition of Cosmic Rays Above 1 TeV per Nucleon," ibid., vol. 2, p.57-60.

Asakimori K., J. W. Watts," Cosmic Ray Composition and Spectra: (1) Protons," in 23rd International Cosmic Ray Conference, Conference Papers, vol. 2, p. 97-99, Calgary, Alberta, Canada.

Asakimori K., J. Arafune, J. W. Watts, "The Super-JACEE Experiments," AIAA Space Programs and Technologies Conference `93-4292, Huntsville Al., Sept. 21-23,1993

Asakimori K., J. Arafune, J. W. Watts," The Super-JACEE Experiments," 23rd International Cosmic Ray Conference, Calgary 93, Poster Session (unpublished), Calgary, Alberta, Canada, July 19-30,1993

Robert M. Winglee

<u>Associate Professor</u>

Geophysics Program, Box 351650
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Ph. D., University of Sydney, 1984
B. Sc. (Hons.), University of Sydney, 1980

Dr. Winglee has extensive experience in space plasma physics, particularly in relation to the Earth's magnetosphere and to the solar corona. Significant areas of research include the generation of auroral kilometric radiation, heating of ionospheric ions in the auroral zone, the active injection of beams from spacecraft, reconnection in the magnetotail and magnetopause, and modeling acceleration processes during solar flares. Particle and fluid simulations have been used extensively to quantitatively determine mechanisms for ion and electron heating and acceleration and the characteristics of the induced currents and wave emissions. The research also utilizes comparative studies with satellite data, including Dynamics Explorer I, Solar Maximum Mission. Recent research has utilized data from Wind and Polar spacecraft in conjunction with global multi-fluid modeling to investigate the specific roles the solar wind and ionospheric sources in the mass loading of the magnetosphere. Dr. Winglee has also been the editor of two conference proceedings and has published or submitted for publication nearly 100 papers. He is presently the Space Physics and Aeronomy Editor for *Geophysical Research Letters.* He is also lead investigator on the development of a new type of plasma propulsion for spacecraft that has received international attention.

PROFESSIONAL CHRONOLOGY (Last 10 yrs): 9/00 - to present, Professor, Geophysics Program, Univ. of Washington; 9/96 - 9/00, Assoc. Professor, Geophysics Program, Univ. of Washington; 01/00 - present, Adjunct Professor, Aeronautics and Astronautics; 12/99 - present, Adjunct. Professor, Dept. of Astronomy, Univ. of Washington; 5/93-present, Adjunct. Professor, Dept. of Physics, Univ. of Washington; 12/91 - 9/96, Assist. Professor, Geophysics Program, Univ. of Washington; 5/91 - 12/91, Professional Scientist, Department of Space Sciences, Southwest Research Institute; 12/89 - 4/91 Senior Research Associate, Department of Astrophysical, Planetary and Atmospheric Sciences, University of Colorado at Boulder.

FIVE RECENT PUBLICATIONS IN SPACE PHYSICS:

Winglee, R. M., Multi-fluid simulations of the magnetosphere: The identification of the geopause and its variation with IMF, *Geophys. Res. Lett., 25,* 4441, 1998.

Winglee, R. M., Imaging the Ionospheric and Solar Wind Sources in the Magnetosphere Through Multi-Fluid Global Simulations, *Physics of Space Plasmas, 15,* 345, 1998.

Li, Q., R. M. Winglee, M. Wilber, L. Chen, and G. Parks, The Geopause in Relation to the Plasma Sheet and Low Latitude Boundary Layer: Comparison Between Wind Observations and Multi-Fluid Simulations, *J. Geophys. Res. 105,* 2563 , 2000.

Winglee, R. M., Mapping of ionospheric outflows into the magnetosphere for varying IMF conditions, *J. Atmos., Solar Terrestrial Physics, 62,* 527, 2000.

Winglee, R. M., J. Slough, T. Ziemba, and A. Goodson, Mini-magnetospheric plasma propulsion: Tapping the energy of the solar wind for spacecraft propulsion, *J. Geophys. Res., 105,* 21,067, 2000.